UNCLASSIFIED

AD 117564

Armed Services Technical Information Agency

Reproduced by

DOCUMENT SERVICE CENTER

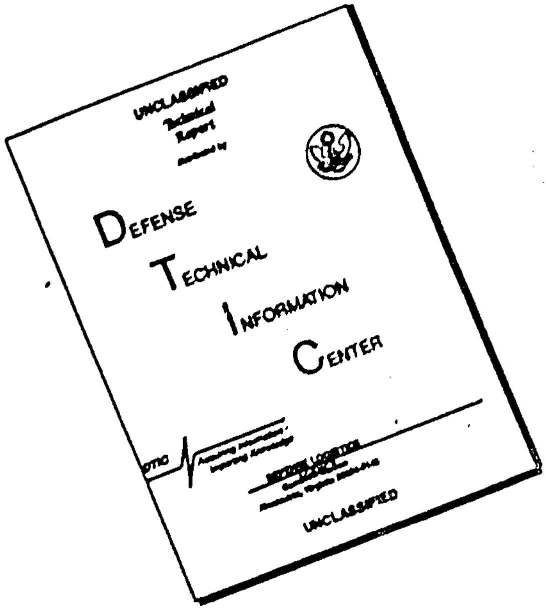
KNOTT BUILDING, DAYTON, 2, OHIO

This document is the property of the United States Government. It is furnished for the duration of the contract and shall be returned when no longer required, or upon recall by ASTIA to the following address: Armed Services Technical Information Agency, Document Service Center, Knott Building, Dayton 2, Ohio.

NOTICE: WHEN GOVERNMENT OR OTHER DRAWINGS, SPECIFICATIONS OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY RELATED GOVERNMENT PROCUREMENT OPERATION, THE U. S. GOVERNMENT THEREBY INCURS NO RESPONSIBILITY, NOR ANY OBLIGATION WHATSOEVER; AND THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED, FURNISHED, OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA IS NOT TO BE REGARDED BY IMPLICATION OR OTHERWISE AS IN ANY MANNER LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION, OR CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

UNCLASSIFIED

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

117564

AD No.
ASTIA FILE COPY

U.S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

FC

U.S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aeronautical Electronic and Electrical Laboratory

REPORT NO. NADC-EL-54129 13 AUG 1956

THEORY, DESIGN AND ENGINEERING EVALUATION OF RADIO-FREQUENCY SHIELDED ROOMS

BUREAU OF AERONAUTICS
TED Project No. ADC EL-538

Reported by: C. S. Vasaka

C. S. Vasaka, Section Head
Interference Control

Approved by: Harry Vantine Jr.

H. Vantine Jr., Superintendent
Radio Division

G. F. Sauter

G. F. Sauter
Deputy Director

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

REPORT NO. NADC-EL-54129

SUMMARY

For the purpose of investigating and compiling specifications for r-f shielded enclosures in general, and in order to evaluate fully a new and improved takedown, cell-type, screen room developed by the U. S. Naval Air Development Center (NADEVCEN), the Bureau of Aeronautics (BUAER) established TED Project No. ADC EL-538, reference (a).

In the course of the project a thorough analysis was made of all available engineering data obtained from the actual use of shielded enclosures and screen rooms. A complete study was also made of the basic theory of shielding and its application to various shielded enclosure designs. Shielding effectiveness of numerous enclosures was tested over a wide range of frequencies and in the presence of various types of fields. Final evaluation of the NADC-AEEL Takedown Cell Type Screen Room was completed.

Results of the project investigations and studies include the following:

1. A presentation of the basic theory of shielding in a form suitable for direct application to the design and construction of shielded enclosures.

2. The preparation of graphs and tables on the shielding effectiveness of solid metal barriers for frequencies from 60 cps to 10,000 mc.

3. The establishment, for the first time, of all the pertinent factors affecting the measurement of the shielding effectiveness of shielded enclosures in the presence of magnetic fields, electric fields, and plane waves.

4. The development of shielding effectiveness test methods that assure repeatable test results under typical laboratory and industrial plant conditions, yet provide a reasonable agreement between enclosure theoretical calculations and actual performance characteristics.

5. The preparation of a service manual on the use, test, and maintenance of shielded enclosures.

6. The compilation of a comprehensive list of available reference material on the construction and use of shielded enclosures.

7. The preparation of a proposed military specification for shielded enclosures and the presentation of recommendations for the establishment of standards and specification requirements for shielded enclosure design, construction, and testing.

8. The promotion of the use and manufacture of cell-type screen rooms and the establishment of the NADC-AEEL Takedown Cell-Type Screen Room as a standard facility for laboratories and industrial plants.

INTRODUCTION

TED Project No. ADC EL-538 was established by Bureau of Aeronautics (BUAER) letter, reference (a), to investigate and compile specifications for r-f enclosures and to evaluate fully the NADC-AEEL Takedown Cell-Type Screen Room. This is a new and improved shielding enclosure developed and used extensively by the Aeronautical Electronic and Electrical Laboratory (AEEL) of the NADEVCEN.

Problem details of the project directive concerned the following:

1. The obtaining of complete data on the shielding effectiveness of the NADC-AEEL Takedown Cell-Type Screen Room for frequencies from 100 kc to 30,000 mc to supplement data given in a preliminary report, reference (b).

2. The determining of any effects caused by aging or by repeated assembly and disassembly of the room.

3. Investigating the room's design characteristics in comparison with those of various other types of shielded enclosures and developing improvements where necessary.

4. Estimating the cost of producing the NADC-AEEL design in comparison with other types of construction.

5. Determining the proper methods for incorporating accessories such as lights, filters, forced ventilation, and other services in the room.

6. Issuing a complete set of detailed engineering drawings of the NADC-AEEL design.

7. Compiling a list of available reference material on shielded enclosures.

This report presents the results of the NADEVCEN investigation of the above problem details. It also presents results of additional NADEVCEN studies and tests which provided the following supplementary information:

1. The applied theory of shielding in a form suitable for use in calculating the shielding effectiveness of various types of shielded enclosures and various shielding materials.

2. Graphs and tables to facilitate shielding effectiveness calculations for various shielding metals.

3. Shielding effectiveness information for frequencies as low as 60 cps.

4. A service manual for cell-type screen rooms.

5. Typical costs of various types of shielded enclosures and power line filters; also a list of shielded enclosure suppliers.

6. A detailed test method (in the absence of any recognized standard method) for measuring the shielding effectiveness of shielded enclosures over the entire r-f spectrum and in the presence of magnetic fields, electric fields, or plane waves.

7. Requirements and recommendations for use in the preparation of military specifications for shielded enclosures.

The NADC-AEEL Takedown Cell-Type Screen Room described in this report represents the end result of a design development started in 1946, reference (b), and kept active by numerous improvements and by a continuing evaluation based on actual use of the room. The basic room design was originated by Rensselaer Polytechnic Institute, reference (c), for use in the shielding of diathermy equipment. The NADEVCEN modified the Rensselaer design to adapt the room for general shielding applications and to improve its performance. These modifications included: (1) lower impedance bonds between component panels of the room through the use of an improved method of panel bolting; (2) provision for bolting floor panels together from inside the room; (3) a completely redesigned door and doorframe with r-f leakproof closure arrangements; (4) improved power line filters, with input and output decoupling, and an improved method of filter installation; (5) provision for entry of various room services such as water, gas, and air lines; r-f transmission lines; rotating-shaft motive power; forced-air ventilation.

Design and construction of the NADC-AEEL Takedown Cell-Type Screen Room was directed toward the following applications:

1. The conducting of radio interference suppression tests in accordance with the rigid requirements of military specifications such as JAN-I-225, MIL-I-6181, 16E5(Aer), 16E4(Ships), AN-I-27, etc.

2. The conducting of tests to determine the radio interference susceptibility of electronic equipment.

3. The r-f calibration and alignment of electronic equipment.

4. Spurious radiation testing of receivers and transmitters.

5. The isolating of test signals to prevent malfunctioning of electronic equipment outside the test area.

6. Production testing and quality control of electronic equipment in industrial plants.

During the development program NADEVCEN promoted the use of cell-type screen rooms; provided technical assistance on screen room problems for the military and for private industry; and encouraged several manufacturers in becoming screen room suppliers.

SECTION I

THEORETICAL CONSIDERATIONS

FORMULAS FOR CALCULATING THE SHIELDING EFFECTIVENESS OF A SINGLE SOLID METAL SHIELD TO WAVES IN SPACE

General

The following formulas present a summary of the theory of shielding in a form suitable for calculating the expected shielding effectiveness of shielding enclosures. The formulas are included in or derived from material contained in references (d), (e), or (f). This reference material provides a complete theoretical analysis of transverse electromagnetic wave transmission as applied to shielding. The analysis considers two current filaments encased in a cylindrical shield (or a point source at the center of a spherical shield) surrounded by free-space conditions. However, the analysis also provides a satisfactory approximation for use in determining the shielding effectiveness offered by plane-surface shields under limited free-space conditions. During the investigations and tests of this project it was found that inaccuracies resulting from use of the approximation are not too prounounced since, in most practical cases, the signal source is not in the immediate vicinity of the shield and the pick-up antenna is small in comparison with the shield size.

The term "solid," as applied to metal shields in this and subsequent sections of the report, is used to denote unperforated metal sheet as opposed to screening material and hardware cloth.

The terms "electric field" and "magnetic field" are used in this report to designate an electromagnetic induction field at a distance from the signal source of much less than a wavelength. Electric fields and magnetic fields are caused by high- and low-impedance sources, respectively. In an electric field the electric component is large and the magnetic component is negligible. In a magnetic field the magnetic component is large and the electric component negligible. Referred to the 377-ohm impedance of plane waves, the impedance for electric fields is higher than 377 ohms and the impedance for magnetic fields is lower than 377 ohms.

Definition of Symbols

R = Total reflection loss in db; i.e., the loss sustained by the incident wave through reflections from both surfaces of the shield. (Multiple reflections inside the shield are neglected.)

A = Penetration loss in db; i.e., the absorption loss sustained by the incident wave in penetrating the shield.

B = A factor calculated in db that compensates for wave reflections inside the shield. It is applied only when A is less than 10 db.

S = Shielding effectiveness in db.

= R + A + B.

= the insertion loss. (See page 25 for complete definition of S.)

Z_s = Intrinsic impedance of metal in vector form.

Z_w = Impedance of incident wave in vector form.

μ = Relative magnetic permeability referred to free space

= 1 for copper.

= 1000 for ferrous metals at low frequencies.

= 1 for ferrous metals at microwave frequencies.

μ_0 = Permeability of free space.

$= 1.26 \times 10^{-6}$ henries/meter $\approx \frac{120\,\pi}{V}$

ϵ = Permitivity of free space

$= 8.85 \times 10^{-12}$ farads/meter $\approx \frac{1}{120\,\pi\, V}$

V = Velocity of light in free space.

= 300,000,000 meters/second.

$= f \times \lambda$.

G = relative conductivity referred to copper.

= 1 for copper.

= 0.17 for iron.

f = Frequency in cycles/second.

λ = wavelength in meters/cycle.

α = Attenuation constant in nepers/meter.

$\beta = \frac{2\pi}{\lambda}$ in radians/meter.

$\omega = 2\pi f$.

r = Distance from source to shield in meters.

r_1 = Distance from source to shield in inches.

E,H = Electric intensity in volts/meter and magnetic intensity in amperes/meter, respectively, transverse to the line of propagation.

t = Thickness of shield in mils.

T = Thickness of shield in meters.

$\sqrt{\frac{\mu_0}{\epsilon}}$ = 376.7 ohms = impedance of plane waves in free space $\approx 120\pi$.

<u>To Find R</u>

As indicated in reference (d)

$$R = 20 \log_{10} \left| \frac{(Z_s + Z_w)^2}{4 Z_s Z_w} \right| \text{ in db} \tag{1}$$

$$Z_s = (1 + j)\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7} \text{ ohms} \tag{2}$$

$$|Z_s| = \sqrt{\frac{\mu f}{G}} \times 3.69 \times 10^{-7} \text{ ohms} \tag{3}$$

R may be zero, positive, or negative, depending on whether the magnitude of the above ratio is equal to, greater than, or smaller than unity. The corrected total reflection = R + B (algebraic sum) and it can be zero, or positive, or negative. B can be zero, positive, or negative. S = R + A + B is positive and always greater than zero.

<u>To Find Z_w for High Impedance Source</u>

Considering a very short nonresonant dipole, length $\ll \lambda$, and using the expressions in reference (e),

$$Z_w = \frac{E}{H} = \frac{1}{V\epsilon} \times \frac{\frac{-\lambda}{2\pi r} + \frac{j\lambda^2}{4\pi^2 r^2} + \frac{\lambda^3}{8\pi^3 r^3}}{\frac{-\lambda}{2\pi r} + \frac{j\lambda^2}{4\pi^2 r^2}} \tag{4}$$

$$= \frac{1}{V\epsilon} \times \frac{1 + j\beta - \beta^2 r^2}{j\beta r - \beta^2 r^2} \tag{5}$$

$$\text{if } r \gg \lambda \text{ then } Z_w = \frac{1}{V\epsilon} = 376.7 \text{ ohms} \tag{6}$$

$$\text{if } r \ll \lambda \text{ then } Z_w = -j\frac{1}{\omega\epsilon r} \text{ ohms} \tag{7}$$

$$= -j\frac{0.71 \times 10^{12}}{f\ r_1} \text{ ohms} \tag{8}$$

To Find Z_W for Low Impedance Source

Considering a very small loop, diameter $\ll \lambda$, and using the expressions in reference (e)

$$Z_W = \frac{E}{H} = V\mu_o \quad x \quad \frac{\frac{-\lambda}{2\pi r} + \frac{j\lambda^2}{4\pi^2 r^2}}{\frac{-\lambda}{2\pi r} + \frac{j\lambda^2}{4\pi^2 r^2} + \frac{\lambda^3}{8\pi^3 r^3}} \quad (9)$$

$$= V\mu_o \quad x \quad \frac{j\beta r \quad - \quad \beta^2 r^2}{1 + j \quad r - \beta^2 r^2} \text{ ohms} \quad (10)$$

if $r \gg \lambda$ then $Z_W = V\mu_o = 376.7$ ohms (11)

if $r \ll \lambda$ then $Z_W = + j\omega\mu_o \gamma$ ohms (12)

$$= + j\ 0.2 \times 10^{-6} f\ r_1 \text{ ohms} \quad (13)$$

R for Plane Waves

Substituting in equation (1), when $r \gg \lambda$

$$R = 20 \log_{10} \frac{\left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7} + 376.7\right)^2 + \left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7}\right)^2}{4 \times \sqrt{\frac{\mu f}{G}} \times 3.69 \times 10^{-7} \times 376.7} \quad (14)$$

Because 376.7 $\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7}$ for all cases

$$R = 20 \log_{10} \frac{376.7}{4 \times 3.69 \times 10^{-7}} \times \sqrt{\frac{G}{\mu f}} \quad (15)$$

$$R = 108.2 + 10 \log_{10} \frac{G \times 10^6}{\mu f} \quad (16)$$

R for Magnetic Fields

Substituting in equation (1), when $r \ll \lambda$

$$R = 20 \log_{10} \frac{\left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7}\right)^2 + \left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7} + 0.2 \times 10^{-6} f\, r_1\right)^2}{4 \times \sqrt{\frac{\mu f}{G}} \times 3.69 \times 10^{-7} \times 0.2 \times 10^{-6}\, f\, r_1} \tag{17}$$

or

$$R = 20 \log_{10} \quad 0.462 \left[\sqrt{\frac{\mu}{Gf}} + 0.136 \sqrt{\frac{Gf}{\mu}} + 0.354\right] \tag{18}$$

R for Electric Fields

Substituting in equation (1), when $r \ll \lambda$

$$R = 20 \log_{10} \frac{\left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7}\right)^2 + \left(\sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7} - \frac{0.71 \times 10^{12}}{f\, r_1}\right)^2}{4 \times \sqrt{\frac{\mu f}{G}} \times 3.69 \times 10^{-7} \times \frac{0.71 \times 10^{12}}{f\, r_1}} \tag{19}$$

Because in all cases $\frac{0.71 \times 10^{12}}{f\, r_1} \gg \sqrt{\frac{\mu f}{2G}} \times 3.69 \times 10^{-7}$

$$R = 20 \log_{10} \; 0.048 \times 10^{19} \sqrt{\frac{G}{f^3 \mu r_1^{\,2}}} \tag{20}$$

$$R = 353.6 + 10 \log_{10} \frac{G}{f^3 \mu r_1^{\,2}} \tag{21}$$

To Find A

As indicated in references (d) and (f),

$$A = 3.338 \times 10^{-3} \times t \sqrt{fG\mu} \tag{22}$$

To Find B

As indicated in references (d) and (f),

$$B = 20 \log_{10} \left| 1 - \left(\frac{Z_s - Z_w}{Z_s + Z_w}\right)^2 e^{-2(\alpha + j\beta)T} \right| \tag{23}$$

which can be expressed as

$$B = 20 \log_{10} \left| 1 - \left(\frac{Z_s - Z_w}{Z_s + Z_w}\right)^2 \times \frac{1}{10^{\frac{A}{10}}} \times \left(\cos 7.68 \times 10^{-4} t \sqrt{f\mu G} - j \sin 7.68 \times 10^{-4} t \sqrt{f\mu G}\right) \right| \quad (24)$$

If $A > 10$ then B becomes negligible.

ANALOGY OF SHIELDING TO TRANSMISSION LINES

An analysis can be made of the shielding effectiveness of single or double shields by considering the case to be analogous to discontinuities in a transmission line. Such an analogy is shown in figures 1 and 2. Except for ℓ, the distance between shields in meters, in figure 2, the symbols in the figures are those defined in the preceding formulas section. For double shields, the metal thickness is assumed to be such as to provide greater than 10 db penetration loss per shield. In comparisons between single shields and double shields the metal thickness of the single shield is assumed to be twice that of the individual barriers of the double shield. The losses in air are neglected.

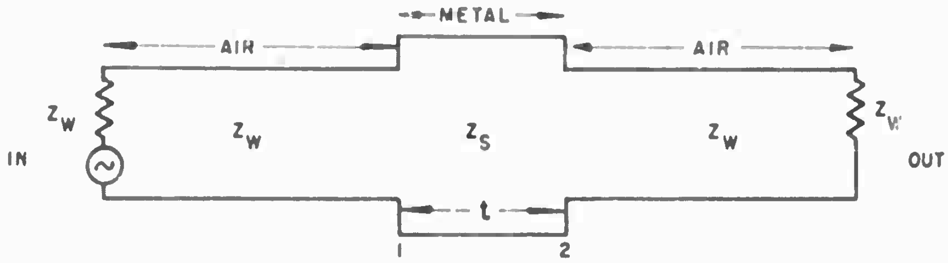


FIGURE 1 - Analogy of Single Shield to Transmission Lines

Single Shield

A single solid metal barrier can be represented as shown in figure 1, and all of the preceding formulas for the expression of R, B, and S can be determined directly by use of standard transmission-line equations.

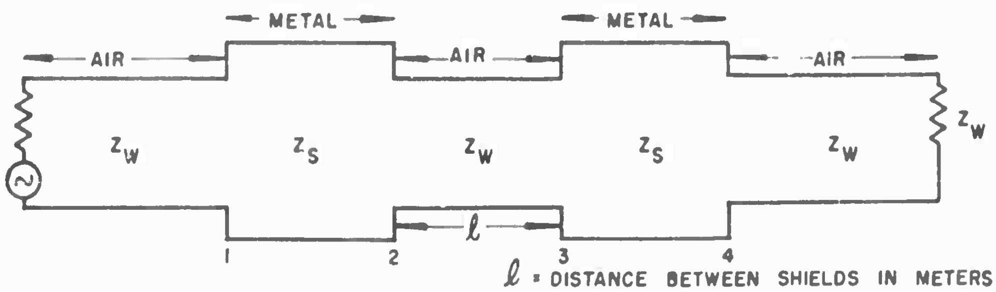


FIGURE 2 - Analogy of Double Shield to Transmission Lines

Double Shield

Two solid metal barriers can be represented as shown in figure 2. The expression for R is exactly the same as in equation (1), the separation of the shields being disregarded

momentarily. There is no necessity to apply the correction factor B because, as stated above, the assumed shield thickness is such that the penetration loss A is greater than 10 db in each shield and is applied separately for each shield as shown in equation (22). To obtain S, however, it is necessary to correct for the additional reflection caused by the separation of the shields. This correction factor, a satisfactory expression for which could not be found in any available reference material, will be designated as R'. S will be expressed as R + A + B + R'.

By use of transmission-line equations the separation between shields can be considered to consist of a known discontinuity, such as a transmission line of length ℓ and known characteristic impedance Z_w, inserted in an original transmission line of characteristic impedance Z_s. The insertion loss due to reflection becomes R' and can be calculated in accordance with the following formula developed by NADEVCEN:

$$R' = 10 \log_{10} \left| \left[\cos \beta\ell + \frac{j}{2}\left(\frac{Z_s}{Z_w} + \frac{Z_w}{Z_s}\right) \sin \beta\ell \right]^2 \right| \tag{25}$$

The derivation of this expression is as follows:

Z_2 = Impedance at point (2) of figure 2, looking to the right

$$Z_2 = Z_w \times \frac{Z_s \cos \beta\ell + j\, Z_w \sin \beta\ell}{Z_w \cos \beta\ell + j\, Z_s \sin \beta\ell}$$

E_s = Sending-end voltage at point (2)

$$E_s = \frac{E\, Z_2}{Z_s + Z_2}$$

(E being the open circuit voltage at point (2) if the length ℓ of Z_w were disconnected)

E_{r_2} = Receiving-end voltage at point (3) of figure 2 with air space present

$$E_{r_2} = \frac{E_s}{\cos \beta\ell + j \frac{Z_w}{Z_s} \sin \beta\ell}$$

E_{r_1} = Receiving-end voltage at point (3) without air space

$$E_{r_1} = \frac{E}{2}$$

Insertion voltage ratio due to air-space reflection

$$= \frac{E_{r_1}}{E_{r_2}} = \frac{\left(Z_s + Z_w \dfrac{Z_s \cos\beta\ell + j Z_w \sin\beta\ell}{Z_w \cos\beta\ell + j Z_s \sin\beta\ell}\right)\left(\cos\beta\ell + j\dfrac{Z_w}{Z_s}\sin\beta\ell\right)}{2 Z_w \dfrac{Z_s \cos\beta\ell + j Z_w \sin\beta\ell}{Z_w \cos\beta\ell + j Z_s \sin\beta\ell}}$$

$$= \frac{Z_s \cos\beta\ell + j Z_w \sin\beta\ell}{2 Z_s} + \frac{Z_w \cos\beta\ell + j Z_s \sin\beta\ell}{2 Z_w}$$

$$= \frac{\cos\beta\ell}{2} + \frac{\cos\beta\ell}{2} + j\frac{Z_w}{2 Z_s}\sin\beta\ell + j\frac{Z_s}{2 Z_w}\sin\beta\ell$$

$$= \cos\beta\ell + \frac{j}{2}\left(\frac{Z_s}{Z_w} + \frac{Z_w}{Z_s}\right)\sin\beta\ell$$

R' = Insertion loss in db

$$= 10\log_{10}\left|\left[\cos\beta\ell + \frac{j}{2}\left(\frac{Z_s}{Z_w} + \frac{Z_w}{Z_s}\right)\sin\beta\ell\right]^2\right|$$

The above formula is an expression for the effect of separating two solid metal shields when the penetration loss in each is over 10 db. This expression can now be considered for various types of fields as follows:

For Plane Waves

$$R' = 10\log_{10}\left[\left(\cos\beta\ell + \frac{b}{4a}\sin\beta\ell\right)^2 + \left(\frac{b}{4a}\sin\beta\ell\right)^2\right] \tag{26}$$

where

$$a = \frac{|Z_s|}{\sqrt{2}}\ ; \quad b = 377 \text{ and } b \gg a \text{ in all cases.}$$

By differentiating equation (26) it can be shown that R' will be:

$$\text{Maximum of } 10\log_{10}\frac{b^2}{8a^2} \text{ when } \beta\ell = \left[(2n+1)\frac{\pi}{2} - \text{arc sin}\frac{2a}{b}\right] \tag{27}$$

indicating a gain in shielding effectiveness.

$$\text{Minimum of } -3 \text{ db when } \beta\ell = \left[(n+1)\pi - \text{arc sin}\frac{2a}{b}\right] \tag{28}$$

indicating an actual loss in shielding effectiveness.

Because $b \gg a$, arc sin $\frac{2a}{b}$ is negligible. For double-shield enclosures with relatively close shield spacing (1 to 4 inches), R' contributes considerable gain in shielding effectiveness at frequencies below 1000 mc but, as shown in the formula, maximum and minimum R' can exist only at microwave frequencies, the region where the shield spacing equals an odd multiple of $\lambda/4$ and a multiple of $\lambda/2$, respectively.

For Magnetic Fields

$$R' = 10 \log_{10} \left[\left(\cos\beta\ell - \frac{b}{4a} \sin\beta\ell \right)^2 + \left(\frac{b}{4a} \sin\beta\ell \right)^2 \right] \tag{29}$$

where

$$a = \frac{|Z_s|}{\sqrt{2}}; \; b = |Z_w| \text{ and } b \gg a \text{ in all cases.}$$

For a spacing of $\ell = 1$ inch the formula reduces:

$$R' = 10 \log_{10} \left[\left(1 - 1.225 \times 10^{-9} \sqrt{\frac{G}{\mu}} \times f^{3/2} \right)^2 + \left(1.225 \times 10^{-9} \sqrt{\frac{G}{\mu}} \times f^{3/2} \right)^2 \right] \tag{30}$$

By differentiating it can be shown that there is a

Minimum of -3 db when

$$f = 0.408^{2/3} \times 10^6 \times \left(\frac{\mu}{G} \right)^{1/3} \tag{31}$$

For Electric Fields

$$R' = 10 \log_{10} \left[\left(\cos\beta\ell + \frac{b}{4a} \sin\beta\ell \right)^2 + \left(\frac{b}{4a} \sin\beta\ell \right)^2 \right] \tag{32}$$

where

$$a = \frac{|Z_s|}{2}; \; b = |Z_w| \text{ and } b \gg a \text{ in all cases.}$$

For a spacing of $\ell = 1$ inch, the formula reduces to

$$R' = 152.56 + 10 \log_{10} \frac{G}{f\mu} \tag{33}$$

which indicates that there is no maximum or minimum.

The formula for the reflection loss caused by shield separation, as given in equation (25), is considered to have been proved experimentally for plane waves at microwave frequencies on the basis of measurements made at NADEVCEN with the NADC-AEEL Cell-Type Screen Room. The data are included in this report. In these measurements, the maximum and minimum reflections caused by varying the spacing of the two shields were readily determined. Although the -3 db reflection points were not determined quantitatively, there is no doubt as to their existence since they constitute instances where wave impedance is exactly the conjugate of load impedance making for maximum power transfer and representing a transmission gain of 3 db as compared with the transmission at the nonreflection frequency where the two impedances are equal to one another vectorically.

An attempt was made at NADEVCEN to prove the shield separation effect of equation (25) for magnetic fields at low frequencies. Two sheet metal boxes were constructed to serve as miniature double-shield enclosures, one with the shields separated and one with the shields touching (zero separation ℓ). The boxes were fabricated from the same guage metal and each shield of both boxes provided better than 10 db penetration loss. The two shields were formed into an electrically-bonded laminate for the box with zero shield separation. Box-within-a-box construction was used for the box with the separated shields. The test setup included a magnetic-field source, outside the boxes, and small pick-up loops inside the boxes. Each loop was connected to measuring instruments located inside a cell-type screen room.

It proved impossible to perform the test because leakage through the screen room was found to be greater than the leakage through either of the boxes and it was determined that satisfactory execution of such a test would require much larger (room-size) enclosures, a stronger signal source, and better shielding for the measuring instruments. Nevertheless, it is considered reasonable to allow the existence of the -3 db reflection loss at some low frequency because of the maximum power transfer consideration at the frequency where the two impedances are conjugate to each other.

Although equation (25) was developed for solid shields with at least 10 db penetration loss, some additional reflection loss tests were made using enclosures of 22-mesh screening material of less than 10 db penetration loss. As before, magnetic fields at low frequencies were used. Tests were made on two small boxes constructed of screening material and also on one of the panels of an assembled double-shield screen room. The boxes were of similar construction to the sheet metal boxes described above and a similar test setup was used. A pick-up antenna was located inside the screen room for the test of the screen room panel.

In the tests with the screen room panel, the spaced inside and outside screens were pushed together (screens touching) and then stretched apart (maximum screen separation) for comparative measurements. At frequencies as low as 100 kc, a 6-db increase in shielding effectiveness was produced in going from the screen-touching position to the maximum screen-separation position. Tests with the screened boxes showed a 10-db increase in shielding effectiveness for the box with the spaced shields as compared with the box with the shields touching. The test results indicated that equation (25) apparently does not apply for screening material of less than 10-db penetration loss. However, the results were not considered conclusive and, as in the case of the tests with the sheet metal boxes, the validity of the equation for these fields, frequencies, and materials remains to be tested with much larger (room-size) enclosures. The considerable increase in shielding effectiveness produced by shield separation for electric fields, as shown in the formula of equation (25), is considered to be self evident.

The preceding formulas (25) through (33) were developed on the assumption that penetration loss A in each solid metal shield is greater than 10 db, which is true in most practical cases under consideration. Where A is less than 10 db, all these formulas have to be corrected and the general formula (25) has to be derived by first expressing the impedances (looking toward the load at points (1), (2), and (3) of figure 2) in the general form as follows:

$$Z_{in} = Z_o \times \frac{Z_{out} \cosh_{\gamma} l + Z_o \sinh_{\gamma} l}{Z_{out} \sinh_{\gamma} l + Z_o \cosh_{\gamma} l} \tag{34}$$

where

$\gamma = a + j\beta$ and Z_o = characteristic impedance.

When A is less than 10 db the calculations in equations (1) and (23) for R and B also require similar correction for the cases involving two shields. Because of the complexities involved, all of these corrections have not been worked out and new formulas remain to be developed for solid metal barriers of less than 10-db penetration loss and for barriers made of screening material. In developing these formulas it may be found necessary to make several approximations to reduce the complexity of the expression for the insertion loss caused by shield separation.

The foregoing analysis of shielding effectiveness has been confined to the various cases of transverse electromagnetic fields; radial fields have not been dealt with since they are seldom encountered in shielded enclosure environments. It can be said, however, that the shielding effectiveness of an enclosure will be much higher for radial electric fields than for transverse electric fields and, conversely, shielding effectiveness will be somewhat lower for radial magnetic fields than for transverse magnetic fields. (See reference (g) for a limited analysis of shielding effectiveness for radial fields.) These differences in the shielding effectiveness of an enclosure for transverse and radial type fields are the result of differences in the reflection loss component alone; the penetration loss component is identical for both types.

CALCULATIONS AND ANALYSIS OF SHIELDING EFFECTIVENESS FOR COPPER AND IRON SHIELDS

Calculations

The expected shielding effectiveness of copper and iron can be calculated for use in the construction of shielded enclosures by means of the formulas presented previously. Calculated data prepared during the investigations of this project are presented for ready reference in the following tables (I through XI) and in figure 3. In the calculations pertaining to iron, the relative permeability μ was taken to be nominal and was based on information included in references (h), (i), (j), (k), and (l).

TABLE I

PENETRATION LOSS - SINGLE SOLID METAL SHIELD

Frequency	Material				Penetration Loss/Mil Thickness (db)	
	Copper		Iron			
	σ	μ	σ	μ	Copper	Iron
60 cps	1	1	0.17	1000	0.026	0.334
1000 cps	1	1	0.17	1000	0.106	1.37
10 kc	1	1	0.17	1000	0.334	4.35
150 kc	1	1	0.17	1000	1.29	16.9
1 mc	1	1	0.17	700	3.34	36.3
15 mc	1	1	0.17	400	12.9	106.0
100 mc	1	1	0.17	100	33.4	137.0
1500 mc	1	1	0.17	10	129.0	168.0
10,000 mc	1	1	0.17	1	334.0	137.0

Note: Other values of μ for iron are 600 at 3 mc, 500 at 10 mc, and 50 at 1000 mc.

TABLE II

REFLECTION LOSS (TOTAL FOR BOTH SURFACES) - SINGLE SOLID METAL SHIELD ELECTRIC FIELDS, WAVE IMPEDANCE $\gg$ 377 OHMS SIGNAL SOURCE 12 INCHES FROM SHIELD

Frequency	Material				Reflection Loss (db)	
	Copper		Iron			
	σ	μ	σ	μ	Copper	Iron
60 cps	1	1	0.17	1000	278.7	241.0
1000 cps	1	1	0.17	1000	242.0	204.4
10 kc	1	1	0.17	1000	212.0	174.0
150 kc	1	1	0.17	1000	176.8	139.0
1 mc	1	1	0.17	700	152.0	116.0
15 mc	1	1	0.17	400	116.9	83.1
100 mc	1	1	0.17	100	92.0	64.4
1500 mc	1	1	0.17	10	*	*
10,000 mc	1	1	0.17	1	*	*

* Above 100 mc the fields approach plane waves with an impedance of 377 ohms. See table III.

Notes:
1. The above table applies for shielding material of sufficient thickness to provide 10 db penetration loss or better. If the penetration loss is < 10 db, the total reflection loss has to be corrected by the B factor as indicated in equation (24).
2. For signal source distances $\gg$ or $\ll$ 12 inches, the reflection loss must be recalculated using formulas given in the text.

TABLE III

REFLECTION LOSS (TOTAL FOR BOTH SURFACES) - SINGLE SOLID METAL SHIELD
PLANE WAVES, WAVE IMPEDANCE = 377 OHMS
SIGNAL SOURCE > 2λ FROM SHIELD

Frequency	Material				Reflection Loss (db)	
	Copper		Iron			
	σ	μ	σ	μ	Copper	Iron
60 cps	1	1	0.17	1000	150.0	112.7
1000 cps	1	1	0.17	1000	138.0	100.5
10 kc	1	1	0.17	1000	128.0	90.5
150 kc	1	1	0.17	1000	117.0	78.8
1 mc	1	1	0.17	700	108.2	72.1
15 mc	1	1	0.17	400	96.4	62.7
100 mc	1	1	0.17	100	88.2	60.5
1500 mc	1	1	0.17	10	76.4	58.8
10,000 mc	1	1	0.17	1	68.2	60.5

Notes: 1. The above table applies for shielding material of sufficient thickness to provide 10 db penetration loss or better. If the penetration loss is < 10 db, the total reflection loss has to be corrected by the B factor as indicated in equation (24).

2. Strong plane waves below 1 mc (with the exception of 550- to 1600-kc radio broadcast signals) seldom exist in the vicinity of a shielded room.

TABLE IV

REFLECTION LOSS (TOTAL FOR BOTH SURFACES) - SINGLE SOLID METAL SHIELD
MAGNETIC FIELDS, WAVE IMPEDANCE ≪ 377 OHMS
SIGNAL SOURCE 12 INCHES FROM SHIELD

Frequency	Material				Reflection Loss (db)	
	Copper		Iron			
	σ	μ	σ	μ	Copper	Iron
60 cps	1	1	0.17	1000	22.4	-0.9
1000 cps	1	1	0.17	1000	34.2	0.9
10 kc	1	1	0.17	1000	44.2	8.0
150 kc	1	1	0.17	1000	56.0	18.7
1 mc	1	1	0.17	700	64.2	28.1
15 mc	1	1	0.17	400	76.0	42.2
100 mc	1	1	0.17	100	84.2	56.5
1500 mc	1	1	0.17	10	*	*
10,000 mc	1	1	0.17	1	*	*

* At these frequencies the fields approach 377 ohms in impedance and become plane waves. See table III.

Notes: 1. The above table applies for shielding material of sufficient thickness to provide 10 db penetration loss or better. If the penetration loss is < 10 db, the total reflection loss has to be corrected by the B factor as indicated in equation (24).

2. The reflection loss for iron is zero at 620 cps and at 60 cps is a negative quantity, calculations indicate that it is again zero at 31.5 cps and then becomes a positive quantity for still lower frequencies.

3. For signal source distances ≫ or ≪ 12 inches, the reflection loss must be recalculated using formulas given in the text.

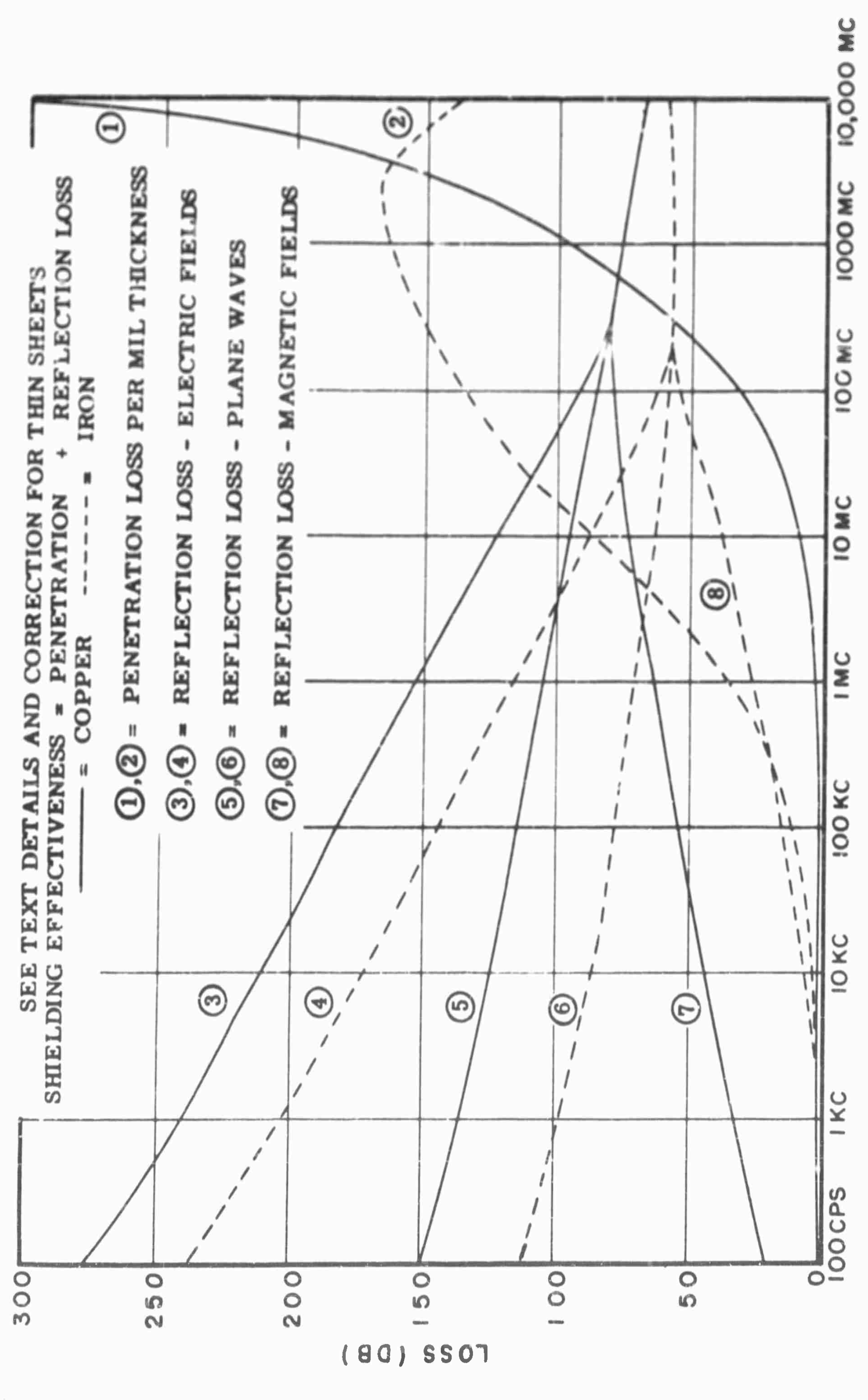


FIGURE 3 - Shielding of Metal Barriers (Graphic representation of data given in Tables I through IV)

TABLE V

B-FACTOR CORRECTION (IN DB) - SINGLE SOLID METAL SHIELD

Shield Thickness (mils)	60 cps	100 cps	1 kc	10 kc	100 kc	1 mc
Copper, μ = 1, G = 1, Magnetic Fields						
1	-22.22	-24.31	-28.23	-19.61	-10.34	-2.61
5	-21.30	-22.07	-15.83	-6.98	-0.55	+0.14
10	-19.23	-18.59	-10.37	-2.62	+0.57	0
20	-15.35	-13.77	-5.41	+0.13	-0.10	
30	-12.55	-10.76	-2.94	+0.58	0	
50	-8.88	-7.07	-0.58	0		
100	-4.24	-2.74	+0.50			
200	-0.76	+0.05	0			
300	+0.32	+0.53				
Copper, μ = 1, G = 1, Electric Fields and Plane Waves						
1	-41.52	-39.31	-29.38	-19.61	-10.33	-2.61
5	-27.64	-25.46	-15.82	-6.96	-0.55	+0.14
10	-21.75	-19.61	-10.33	-2.61	+0.57	0
20	-15.99	-13.92	-5.37	+0.14	-0.10	
30	-12.73	-10.73	-2.90	+0.58	0	
50	-8.81	-6.96	-0.55	+0.14		
100	-4.08	-2.61	+0.51	0		
200	-0.62	+0.14	0			
300	+0.41	+0.58				
Iron, μ = 1000, G = 0.17, Magnetic Fields						
1	+0.95	+1.23	-1.60	-1.83		
5	+0.93	+0.89	-0.59	0		
10	+0.78	+0.48	+0.06			
20	+0.35	+0.08	0			
30	+0.06	-0.06				
50	0	0				
Iron, μ = 1000, G = 0.17, Electric Fields and Plane Waves						
1	-19.53	-17.41	-8.35	-1.31		
5	-6.90	-5.17	+0.20	0		
10	-2.56	-1.31	+0.36			
20	+0.16	+0.54	0			
30	+0.58	+0.42				
50	+0.13	0				

Note: This B-factor correction has to be applied to the reflection loss values shown in tables II, III, and IV when the total penetration loss obtained from table I is < 10 db.

TABLE VI

TYPICAL SHIELDING EFFECTIVENESS CALCULATIONS BASED ON DATA INCLUDED IN TABLES I THROUGH V

Material	Frequency	Type of Field	Metal Thickness (Mils)	R Reflection Loss (db)	A Penetration Loss (db)	B B Factor (db)	Total Shielding Effectiveness S = R+A+B (db)
Copper	60 cps	Magnetic	1	22.4	0.026	-22.2	0.23
	60 cps	Magnetic	10	22.4	0.26	-19.2	3.46
	60 cps	Magnetic	300	22.4	7.80	+0.32	30.52
	1 kc	Magnetic	10	34.2	1.06	-10.37	24.89
	10 kc	Magnetic	10	44.20	3.34	-2.62	44.92
	10 kc	Electric	10	212.0	3.34	-2.61	212.73
	10 kc	Plane Waves	10	128.0	3.34	-2.61	128.73
	10 kc	Magnetic	30	44.20	10.02	+0.58	54.80
	150 kc	Magnetic	10	56.0	12.9	+0.5	69.4
	150 kc	Electric	10	176.8	12.9	+0.5	190.2
	150 kc	Plane Waves	10	117.0	12.9	+0.5	130.4
	1 mc	Magnetic	10	64.2	33.4	0	97.6
	1 mc	Electric	10	152.0	33.4	0	185.4
Copper	1 mc	Plane Waves	10	108.2	33.4	0	141.6
Iron	60 cps	Magnetic	1	-0.9	0.334	+0.95	0.38
	60 cps	Magnetic	10	-0.9	3.34	+0.78	3.22
	60 cps	Magnetic	300	-0.9	100.0	0	99.1
	1 kc	Magnetic	10	0.9	13.70	+0.06	14.66
	10 kc	Magnetic	10	8.0	43.5	0	51.5
	10 kc	Electric	10	174.0	43.5	0	217.5
	10 kc	Plane Waves	10	90.5	43.5	0	134.0
Iron	10 kc	Magnetic	30	8.0	130.5	0	138.5

TABLE VII

RELATIVE CONDUCTIVITY, RELATIVE PERMEABILITY, AND PENETRATION LOSS OF VARIOUS METALS

Metal	Relative Conductivity	Relative Permeability	Penetration Loss/Mil at 150 kc (db)
Silver	1.05	1	1.32
Copper, Annealed	1.00	1	1.29
Copper, Hard-Drawn	0.97	1	1.26
Gold	0.70	1	1.08
Aluminum	0.61	1	1.01
Magnesium	0.38	1	0.79
Zinc	0.29	1	0.70
Brass	0.26	1	0.66
Cadmium	0.23	1	0.62
Nickel	0.20	1	0.58
Phosphor-Bronze	0.18	1	0.55
Iron	0.17	1000	16.9
Tin	0.15	1	0.50
Steel, SAE 1045	0.10	1000	12.9
Berryllium	0.10	1	0.41
Lead	0.08	1	0.36
Hypernick	0.06	80,000	88.5
Monel	0.04	1	0.26
Mu-Metal	0.03	80,000	63.2
Permalloy	0.03	80,000	63.2
Steel, Stainless	0.02	1000	5.7

Note: Use equation (22) for penetration loss at other frequencies.

TABLE VIII

WAVELENGTH OF ELECTROMAGNETIC WAVES IN COPPER AND IRON

Frequency	Wavelength (Mils)	
	Copper	Iron
100 mc	1.64	0.399
10 mc	5.20	0.561
1 mc	16.4	1.51
100 kc	52.0	39.9
10 kc	164	126
1 kc	520	399
100 cps	1640	1260
10 cps	5200	3990

Note: The above values were calculated by use of equation (35).

TABLE IX

REFLECTION LOSS DUE TO SHIELD SEPARATION - ELECTRIC FIELDS
TWO SOLID METAL SHIELDS (1-INCH SEPARATION)
WAVE IMPEDANCE $\gg$ 377 OHMS
SIGNAL SOURCE 12 INCHES FROM SHIELD

Frequency	Reflection Loss (db)	
	Copper	Iron
100 mc	72.56	44.86
10 mc	82.56	47.88
1 mc	92.56	56.42
100 kc	102.56	64.86
10 kc	112.56	74.86
1 kc	122.56	84.86
100 cps	132.56	94.86

Notes: 1. The penetration loss in each shield is taken to be > 10 db.
2. No electric field can exist above 100 mc at a distance of 12 inches from the signal source.

TABLE X

REFLECTION LOSS DUE TO SHIELD SEPARATION - PLANE WAVES
TWO SOLID METAL SHIELDS (1-INCH SEPARATION)
WAVE IMPEDANCE = 377 OHMS
SIGNAL SOURCE $\gg \lambda$ FROM SHIELD

Frequency	Reflection Loss (db)	
	Copper	Iron
10,000 mc *	68.3	61.6
3000 mc **	79.2	71.4
1000 mc	78.1	53.5
100 mc	68.2	41.0
10 mc	58.5	24.2
1 mc	48.6	13.8
100 kc	38.6	5.7
10 kc	28.8	2.1
1 kc	19.3	0.7
100 cps	10.7	0.1

* At 10,000 mc small variations in the nominal 1-inch shield separation from 0.9 inch to 1.2 inch (approximately $\frac{3\lambda}{4}$ to λ) will change the reflection loss for copper from a maximum of 74.2 db to a minimum of -3 db; and the reflection loss for iron from a maximum of 66.5 db to a minimum of -3 db.

** At 3000 mc maximum reflection loss will occur when the shield separation is reduced to 0.985 inch and will be 79.4 db for copper and 71.6 db for iron.

Notes: 1. The penetration loss in each shield is taken to be > 10 db.
2. Strong plane waves below 1 mc (with the exception of 550- to 1600-kc radio broadcast signals) seldom exist in the vicinity of a shielding room.

TABLE XI

REFLECTION LOSS DUE TO SHIELD SEPARATION - MAGNETIC FIELDS
TWO SOLID METAL SHIELDS (1-INCH SEPARATION)
WAVE IMPEDANCE $\ll$ 377 OHMS
SIGNAL SOURCE 12 INCHES FROM SHIELD

Frequency	Reflection Loss (db)	
	Copper	Iron
100 mc	+64.8	+36.9
12.3 mc	*	0.0
10 mc	+34.8	-1.6
8.3 mc	*	-3.0
1 mc	+1.8	-0.0
870 kc	0.0	-0.0
550 kc	-3.0	-0.0
100 kc	-0.34	-0.0
10 kc	-0.0	-0.0
1 kc	-0.0	-0.0
100 cps	-0.0	-0.0

* No readings taken at 12.3 mc and 8.3 mc.

Notes:
1. No magnetic fields can exist above 100 mc at a distance of 12 inches from the signal source.
2. The penetration loss in each shield is taken to be > 10 db.
3. Negative db values indicate an actual decrease in shielding effectiveness.
4. The μ for iron was taken as 475 at 12.3 mc and 550 at 8.3 mc.
5. Values indicated as 0.0 represent negligible quantities.

Analysis

Using the basic formulas given in equations (1) through (34), the following analysis can be made of the shielding effectiveness of various types of shields at various frequencies and in the presence of various types of fields.

1. General

a. Copper and iron are the two most widely-used materials for the construction of shielding enclosures. Other metals, such as aluminum, magnesium, brass, etc., are sometimes used for certain applications because of considerations of cost, weight and availability. When using metals other than copper, however, the achieving of adequate low r-f impedance seams between mating surfaces becomes more difficult because of oxidation and corrosion problems.

b. Magnetic fields are the most difficult fields to shield against.

c. The wavelength of electromagnetic waves is much shorter in metals than in free space (table VIII) as shown in the following formula:

$$\lambda = \frac{0.415}{\sqrt{f \mu G}} \qquad (35)$$

For this reason "electrically-thin" shields (penetration loss $<$ 10 db) can have actual physical thickness that is comparable to the wavelength.

2. Single Solid Barriers

a. At 60 cps it is necessary to use 300-mil iron sheet material of μ = 1000 and G = 0.17 to obtain 100 db shielding effectiveness. Copper sheet would have to be 3.0 inches thick to provide the same shielding effectiveness.

b. The total shielding effectiveness of 20-mil copper or 20-mil iron sheet will increase rapidly above approximately 2 mc and will amount to several hundred db at 10,000 mc. This very high shielding effectiveness at the microwave frequencies is not really needed, but the sheet thickness cannot be decreased without lowering shielding effectiveness at the low end of the frequency range.

c. Iron sheet with a permeability of μ = 1000 is superior to copper sheet from the lowest frequencies well up to 10,000 mc. Above 10,000 mc, however, because the μ for iron becomes unity (while its conductivity remains lower than that of copper), iron is much inferior to copper in shielding effectiveness.

d. If a shield has to be designed to provide a shielding effectiveness of 100 db over as large a frequency range as possible, and if weight and cost of material is not a limiting factor, it is only necessary to calculate for the shield thickness required to provide 100 db penetration loss at the low end of the frequency range. The total shielding effectiveness actually produced (including reflection loss and penetration loss) will be more than 100 db for the entire frequency range considered and will still be 100 db at a frequency somewhat lower than the low-frequency design point. The effect of this is to extend the low end of the frequency range over which a shielding effectiveness of at least 100 db can be realized. This range extension will be larger for copper than for iron.

e. Reflection loss generally can be disregarded in the design of copper or iron shields if sufficient shield thickness can be provided to afford adequate penetration loss for the frequency range considered, and if the design calculations can be confined to penetration loss alone. If the penetration loss realized is above the minimum amount designed for (100 db, or so), the losses due to reflection will only add to it. The additional shielding effectiveness contributed by the reflection loss component will be a minimum for magnetic fields. Consequently, magnetic fields are the most difficult to shield against.

f. The total reflection loss of metals for magnetic fields becomes negligible at frequencies below 1 kc and actually may be a negative quantity. Any shielding effectiveness realized at these frequencies is due mainly to penetration loss. The total shielding effectiveness calculated in db is a positive value in all cases.

g. Copper sheet of 20-mil thickness will provide over 100 db of shielding effectiveness from penetration loss alone at 2.2 mc and above, and a total shielding effectiveness of over 100 db at approximately 500 kc and above. Iron sheet of 20-mil thickness will provide over 100 db of shielding effectiveness from penetration loss alone at 13 kc and above, and a total shielding effectiveness of over 100 db at approximately 12 kc and above.

3. Screening Material

a. The theory and calculations for determining the shielding effectiveness of solid metal shields cannot be applied directly to copper screening material without corrections. This is because the impedance of the screening material is always higher than the intrinsic impedance of solid copper, chiefly due to the effect of small-hole leakage. However, the theoretical formulas and available calculated values for solid metal shields can be used to obtain a rough evaluation of the probable shielding effectiveness offered by screening material and perforated sheet metal. A comparison between actual shielding effectiveness afforded by the NADC-AEEL Cell-Type Screen Room and that calculated for 10-mil solid copper sheet is shown in the following table:

TABLE XII

TOTAL SHIELDING EFFECTIVENESS FOR MAGNETIC FIELDS
NADC-AEEL SCREEN ROOM VS SINGLE SHIELD OF 10-MIL COPPER SHEET

Frequency	22-Mesh, 15-Mil Copper Wire Double-Shield Cell-Type Screen Room	10-Mil Copper Sheet Single Shield
	db (measured)	db (calculated)
10 kc	40	45
150 kc	68	69
1 mc	82	98

These results indicate that the impedance of copper screening is higher than the intrinsic impedance of solid copper sheet, even at low frequencies. It has been contended by some

observers, reference (m), that copper screening of not more than 50 percent open area, and not less than 60 strands per wavelength, has an impedance that approximates the intrinsic impedance of the solid metal. However, actual shielding effectiveness obtained in tests with the cell-type screen room indicate that other factors have to be considered. In these tests the two 15-mil thicknesses of 22-mesh copper screening approximated the attenuation of 10-mil rather than 30-mil solid sheet over a frequency range of from 10 kc to 1 mc.

b. Observers have further contended that copper screening has negligible penetration loss and that the total shielding effectiveness realized is caused principally by reflection loss, even at frequencies as high as 30 mc. Tests made during investigations of this project also show this contention to be in error. It was found that screening material may be considered to be equivalent to a solid copper sheet of a thickness much less than the diameter of the individual wires of the screen mesh, the exact relationship being determined experimentally. Table VI includes instances where the total shielding effectiveness is caused principally by reflection loss as, for example, in the case of magnetic fields and 10-mil copper sheet at 10 kc. However, as shown in the tables and in figure 3, in all cases above 1 mc the penetration loss becomes a large portion of the total shielding effectiveness because of the several mils involved in the thickness of the material. The penetration loss component of the total shielding effectiveness increases greatly as the frequency increases. A similar increase in the penetration loss component should also exist for screening material.

c. Copper screening will have higher impedance and much less shielding effectiveness than solid copper sheet if the open area of the mesh is increased, the wire diameter decreased, or the frequency increased. At frequencies of 30,000 mc and over, a double shield of 22-mesh, 15-mil copper screening will have very little shielding effectiveness.

d. The intrinsic impedance of screening material of a given metal, mesh, or wire diameter cannot be calculated by existing formulas. It can be determined experimentally, however, by actual shielding effectiveness measurements using the screening material in comparison with solid sheet of the same metal. It should be noted that the intrinsic impedance of the screening material will increase with frequency at a much faster rate than will that of the solid sheet material.

4. <u>Shield Separation for Double Shields</u>

a. The increase or decrease in shielding effectiveness contributed by shield separation depends on such factors as frequency, wave impedance, type of shielding material, distance between shields, and shield thickness.

b. In general, shield separation increases shielding effectiveness for both plane waves and electric fields; with a considerable increase for the latter. For magnetic fields, however, shield separation may actually produce a 3-db decrease in shielding effectiveness at some low frequencies.

c. At microwave frequencies, the field can be considered to be that of plane waves and at various frequencies within this region a nominal shield separation of 1 inch will afford maximum shielding effectiveness when the separation becomes an odd multiple of quarter wavelengths. However, there will be a 3-db decrease in shielding effectiveness when the shield separation becomes a multiple of approximate half wavelengths.

d. The shield separation distance for cell-type copper enclosures is usually 1 inch. The effect of increasing the shield spacing to 4 inches, for example, can be calculated by means of equation (25). Essentially, the effect of increasing the shield spacing is to shift (by a factor of 1/4) the particular microwave frequencies where maximum and minimum shielding effectiveness takes place for plane waves, and also to shift (by a factor of 1/2) the particular frequency in the low-frequency region where minimum shielding effectiveness takes place for magnetic fields. However, increasing the shield spacing does not substantially affect the over-all shielding effectiveness.

e. Although experimental proof is lacking, there are indications that at low frequencies (below 1 mc for copper and below 12 mc for iron) cell-type enclosures are superior in shielding effectiveness to isolated-shield enclosures by about 3 db when both types are constructed of solid sheet material affording better than 10-db penetration loss per shield. Any differences in shielding effectiveness between the two enclosure types caused by the use of solid sheet material affording less than 10-db penetration loss per shield, or by the use of screening material, remain to be determined.

f. At intermediate frequencies, the double-shield members of a cell-type screen room are not effectively isolated because the width of each of the room's panels is of the order of a wavelength. The shielding effectiveness of the cell-type room is somewhat less than that produced by the isolated-shield type, but is nevertheless adequate because of the considerable amount of shielding effectiveness contributed by penetration loss alone at these frequencies.

g. At microwave frequencies, the double-shield members of a cell-type screen room are effectively isolated because the width of each of the room's panel sections is much larger than a wavelength. At these frequencies shield separation contributes about the same amount of shielding effectiveness for both cell-type and isolated-shield type screen rooms.

5. Construction Considerations

a. Shielded rooms constructed of solid iron sheet theoretically should have higher shielding effectiveness than those constructed of copper. However, because of the difficulties of achieving adequate seams in iron, the shielding effectiveness actually realized from iron rooms may be lower than that obtained from copper rooms.

b. From a practical standpoint, the spaced double-shield construction of the cell-type screen room offers an extra margin of safety over the single-shield type of room in instances where one of the screens is accidentally punctured.

DEFINITION OF SHIELDING EFFECTIVENESS AND ANALYSIS OF TEST CONDITIONS

Definition

Shielding effectiveness S is properly defined as the insertion loss (in db) in power sustained by an electromagnetic wave at a given point in space when a metal barrier is inserted between the transmitting source and that point. The definition is illustrated in figure 4. Under this definition, the wave impedance at the point of measurement remains the same with the barrier in or out of the signal path and, for this reason, the same shielding effectiveness will be obtained regardless of whether the ratio is taken of real powers, apparent powers, voltages, or currents. The definition is predicated on the conditions

that: (1) the insertion of the meta barrier does not affect the impeda of the source, (2) waves leaving the barrier by ref ction or transmission do not ret n, and (3) the barrier thickness is very much smaller than the distance from the tr smitting source to the barrier.

Therefore, as shown in figure 4,

$$S = 10 \log_{10} \left| \frac{E_1 H_1}{E_5 H_5} \right| = 10 \log_{10} \left| \frac{\dfrac{E_1^{2}}{Z_1}}{\dfrac{E_1^{2}}{Z_1} \dfrac{1}{100} \left[\dfrac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \right]^2} \right|$$

$$= 10 \log_{10} 100 \left| \left[\frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right]^2 \right|$$

$$= 20 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right| + 20 \text{ (penetration loss)}$$

R = the total reflection loss at surfaces (1) and (2) and is equal to

$$R = 20 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right| = \text{approximately } 20 \log_{10} \left| \frac{Z_1}{Z_2} \right|$$

Therefore

$$S = R + A$$

Also, because the wave impedance on both sides of the barrier is the same, S can be calculated as:

$$S = 20 \log_{10} \left| \frac{E_1}{E_5} \right| = 20 \log_{10} \left| \frac{E_1}{\dfrac{E_1}{10} \dfrac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}} \right|$$

$$= 20 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right| + 20$$

As well as:

$$S = 20 \log_{10} \left| \frac{H_1}{H_5} \right| = 20 \log_{10} \left| \frac{\frac{E_1}{Z_1}}{\frac{E_1}{Z_1} \; \frac{1}{10} \; \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}} \right|$$

$$= 20 \log_{10} \left| \frac{(Z_1 + Z_2)}{4 Z_1 Z_2} \right| + 20$$

Similarly, the reflection loss components $R_{(1)}$ and $R_{(2)}$, at surfaces (1) and (2), respectively, will be equal to each other and equal to:

$$R_{(1)} = 10 \log_{10} \left| \frac{E_1 H_1}{E_2 H_2} \right| = 10 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right|$$

$$R_{(2)} = 10 \log_{10} \left| \frac{E_4 H_4}{E_5 H_5} \right| = 10 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right|$$

therefore $R_{(1)} = R_{(2)}$

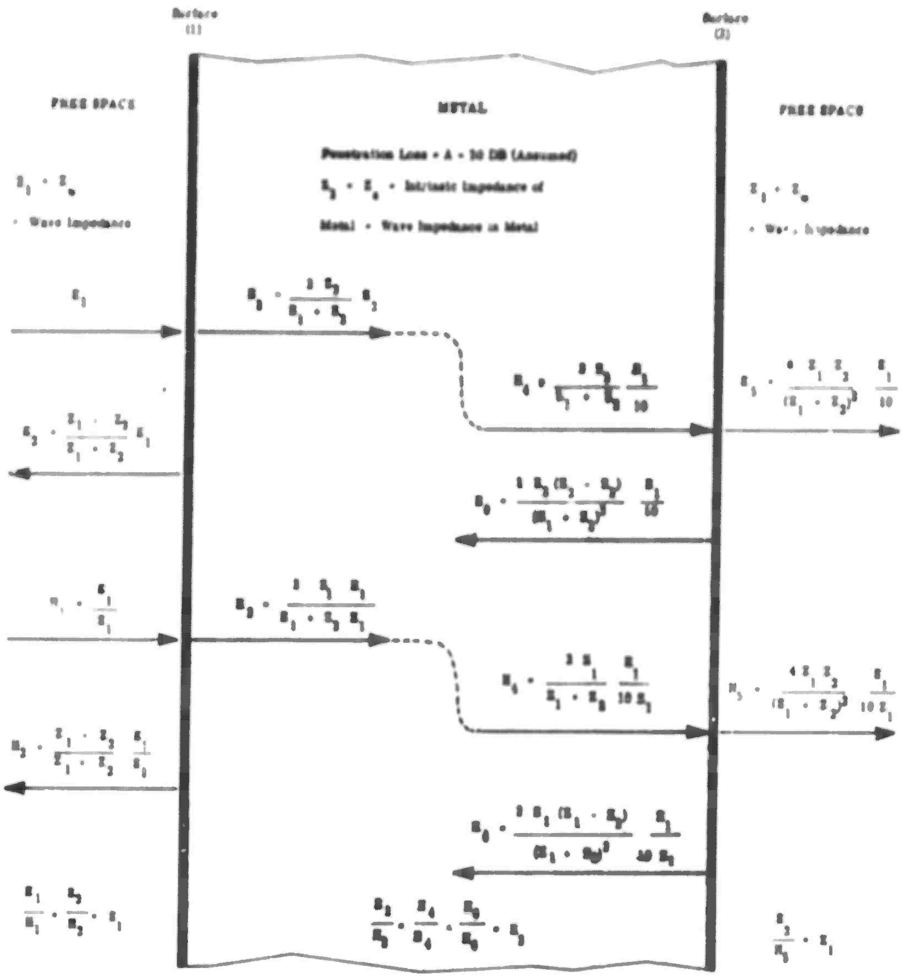
Because

$$R_{(1)} + R_{(2)} = 10 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right| + 10 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right|$$

$$= 20 \log_{10} \left| \frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2} \right|$$

then $R_{(1)} + R_{(2)} = R$

The impedance of the incident wave Z_W changes as the wave is penetrating the metal barrier and assumes the impedance of the metal itself, Z_S. However, after the wave leaves the barrier it assumes its original impedance. This impedance may be very low for magnetic fields (low source impedance), very high for electric fields (high source impedance), and may amount to 376.7 ohms (the impedance of free space) for plane waves. In practically all cases, however, the impedance of the wave is higher than the impedance of the barrier. As stated previously in the insertion-loss definition of shield-effectiveness, the wave impedance at the load (point of measurement) does not change and, therefore, in shielding effectiveness tests it is not necessary to make power measurements because voltage measurements made under the same conditions will provide the same degree of accuracy and are simpler to perform.



S = Shielding Effectiveness in DB

$$S = 20\log_{10}\left|\frac{E_1}{E_5}\right| = 20\log_{10}\left|\frac{H_1}{H_5}\right| = 10\log_{10}\left|\frac{E_1 H_1}{E_5 H_5}\right| = 20\log_{10}\left|\frac{(Z_1+Z_2)^2}{4 Z_1 Z_2}\right| + 20 = R + A$$

Z_1 or Z_w = Wave impedance (376.7 ohms for plane waves). In practically all cases it is higher than Z_2.

Z_2 or Z_s = Intrinsic impedance of the metal. In practically all cases it is lower than Z_1.

E_1 through E_6 and H_1 through H_6 = Electric and magnetic components, respectively, of the various waves. Only magnitudes are shown.

E_1 = Incident wave at surface (1) of barrier.

E_2 = Wave after penetrating surface (1) of barrier. E_2 is greatly reduced in intensity as compared with E_1.

E_3 = Incident wave reflected from surface (1) of barrier. E_3 does not return to barrier.

E_4 = Wave at surface (2) of barrier. E_4 is reduced in intensity to one-tenth that of E_2.

E_5 = Wave leaving surface (2) of barrier. E_5 is practically double the intensity of E_4.

E_6 = Wave reflected from surface (2) of barrier. E_6 is negligible in effect if the penetration loss A is greater than 10 db. If A is less than 10 db, a correction factor B has to be applied as indicated in equation (24).

H_1 = Incident wave at surface (1) of barrier.

H_2 = Wave after penetrating surface (1) of barrier. H_2 is practically double the intensity of H_1.

H_3 = Incident wave reflected from surface (1) of barrier. E_3 does not return to barrier.

H_4 = Wave at surface (2) of barrier. H_4 is reduced in intensity to one-tenth that of H_2.

H_5 = Wave leaving surface (2) of barrier. H_5 is greatly reduced in intensity as compared with H_4.

H_6 = Wave reflected from surface (2) of barrier. H_6 is of negligible effect if the penetration loss A is greater than 10 db. If A is less than 10 db, a correction factor B has to be applied as indicated in equation (24).

FIGURE 4 - Illustrating the Shielding Effectiveness of a Metal Barrier

In making shielding effectiveness tests the voltage induced in the pick-up antenna is first measured with the barrier in effect removed from the signal path, and with the pick-up antenna located at a distance sufficiently removed from the signal source so as not to affect the impedance of the source or the incident wave. The barrier is then inserted between source and pick-up antenna and is so positioned that the Q, effective height, and impedance of the pick-up antenna are relatively unaffected by the shield's proximity. The lowered induced voltage of the pick-up antenna is then measured and the shielding effectiveness equals:

$$S = 20 \log_{10} \frac{e_1}{e_2}$$

where

e_1 = voltage induced in pick-up antenna with barrier removed

e_2 = voltage induced in pick-up antenna with barrier inserted.

Shielding Effectiveness Test Conditions

The foregoing insertion-loss definition and discussion of shielding effectiveness is a theoretical presentation which considers a metal barrier under free space conditions. This situation can never be realized fully in practical shielding applications, and therefore the test method for insertion-loss testing of shielding enclosures and screen rooms is designed for the actual conditions existing inside and outside enclosures in typical laboratory and industrial plant environments. These actual test conditions of necessity constitute wide deviations from the theoretical conditions. Chief among the deviations are the following:

1. Inside a shielding enclosure the medium immediately beyond the barrier is not free space and waves can be returned to the barrier by reflection. The enclosure may become a cavity resonator at several frequencies depending on its shape and size.

2. Free-space conditions rarely exist on the outside of the enclosure and reflections of the incident wave can be returned to the barrier.

3. It is practically impossible to subject an entire enclosure or screen room to a homogeneous field produced by a powerful source located a great distance away, and consequently, nonhomogeneous fields from relatively close sources generally must be used. In some instances, portions of a room must be tested separately.

4. It is generally impractical to literally remove a shielding enclosure or screen room from the signal path for "in" and "out" insertion-loss measurements.

Despite the above deviations from theoretical conditions, the insertion-loss concept of shielding effectiveness can produce a close correlation between the theoretical calculated values and the measured values obtained in actual tests if proper test procedures are employed. Section III of this report presents specific shielding effectiveness test procedures which take into consideration all of the deviations listed above. Section III also includes information for the elimination or large reduction of test-setup systemic errors such as:

1. Wave penetration of test instrument cases and transmission line shields.

2. Nonlinearity of detectors at various signal levels.

3. Changes in input impedance of the instruments.

4. Changes in the impedance and effective height of the pick-up antenna.

5. Variations in wave impedance in the vicinity of shielding enclosures and screen rooms caused by changes in distance relative to the wavelength between signal source and enclosure.

6. Nonlinearity of attenuators used in the test setup.

7. The effect of positioning the transmitting and receiving antennas with respect to the various seams of the enclosure.

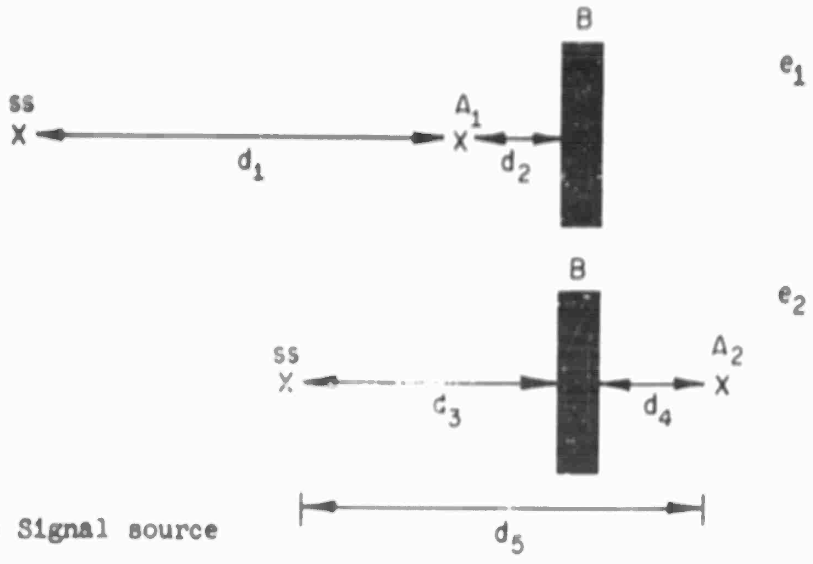
8. Reflections and resonance conditions inside the shielding enclosure influencing the voltages induced in the pick-up antenna.

DESCRIPTION OF INSERTION-LOSS SHIELDING EFFECTIVENESS TEST AND COMPARISON WITH "ATTENUATION" TEST AND SURFACE TRANSFER IMPEDANCE TEST

Of the several methods used or proposed for testing the shielding effectiveness of shielded enclosures and screen rooms, it is felt that the insertion-loss test developed under this project offers the closest correlation between results obtained from theoretical calculations and those obtained in tests of actual enclosures under typical laboratory conditions. The basic features of the test are presented below. (See Section III of this report for complete test procedures.) Two other test methods, the "attenuation" test and the surface transfer impedance test, are also described for comparison purposes. However, these latter methods are not recommended for the reasons given.

Insertion-Loss Test

The insertion-loss test can be applied to shielding enclosures and screen rooms of either single- or double-shield construction. The basic test procedure is illustrated in figures 5 and 6. In applying the arrangement of figure 5 to actual test procedures, distance d_1 is made much less than 1/6 of the wavelength ($\frac{\lambda}{2\pi}$) for electric fields and magnetic fields, and is made as large as possible (within power limits of the signal source) for plane waves. Distance d_2 is made large enough to prevent the characteristics of SS, A_1, or the incident wave from being affected. Distance d_3 is made large enough to prevent the characteristics of SS and the incident wave from being affected. Distance d_4 is made just large enough to prevent the characteristics of A_2 from being affected. Distance d_5 is made equal to D_1. The insertion loss in db = 20 $\log_{10} \frac{e_1}{e_2}$. Measurements at e_1 and e_2 can be measurements of real power, apparent power, voltage, or current; all will give the same results in db because the wave impedance at A_1 and A_2 is the same. In measurement step e_1, barrier B (the enclosure) is utilized to shield the measuring instruments, but is otherwise effectively removed from the signal path.



SS = Signal source

A_1 = Pick-up antenna location for measurement e_1

A_2 = Pick-up antenna location for measurement e_2

B = Barrier (enclosure shield; single- or double-shield type)

e_1 = First measurement (barrier removed)

e_2 = Second measurement (barrier inserted)

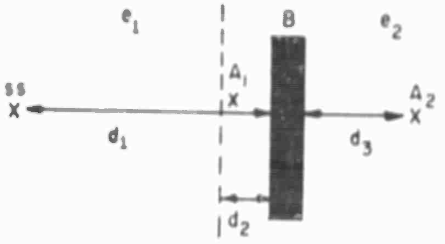
NOTE: d_1 through d_5 represents respective distances shown

FIGURE 5 - Insertion-Loss Test - 150 kc to 20 mc and 1000 to 10,000 mc

The conditions of figure 5 can be readily established for electric fields and magnetic fields, the predominant fields in the vicinity of shielded enclosures up to about 20 mc, and also can be established for plane waves in the microwave region from 1000 to 10,000 mc. Shielding effectiveness values based on measured values for e_1 and e_2 may differ somewhat from calculated values based on the theoretical formulas of figure 4, and on those given previously, but a reasonably close agreement can be obtained if the previously mentioned deviations from theoretical conditions are kept to a minimum by proper test methods. In the 1000- to 10,000-mc region, measurement of the incident wave at e_1 requires the use of directional antennas (for both signal source and receiver) to beam the signals to the enclosure and thus prevent standing waves which otherwise would be caused by signal reflections in the test area. When measuring the shielding effectiveness of double-shield enclosures at these frequencies, the shield-separation distance ℓ should be varied (or the frequency varied) sufficiently to make ℓ become alternately an odd multiple of $\lambda/4$ and a multiple of $\lambda/2$. Theoretically, the total reflection loss R at the two outside surfaces of two solid copper sheets is 68 db at 10,000 mc. However, as discussed earlier, R' can increase this 68-db reflection loss by an additional 74 db when ℓ becomes an odd multiple of $\lambda/4$, and can decrease it by 3 db when ℓ becomes a multiple of $\lambda/2$. These changes in reflection loss must be noted carefully when making shielding effectiveness measurements.

The conditions of figure 5 cannot be established for plane waves at frequencies from 20 to 1000 mc because of power limitations of the signal source and because of the unavoidable existence of standing waves on both sides of the barrier (both inside and outside

the enclosure). Although true incident-wave measurements cannot be made for these frequencies, a satisfactory approximation of the ratio of incident wave to the wave inside the enclosure can be obtained by means of the procedure illustrated in figure 6. In measurement steps e_1 and e_2 of this figure, maximum readings are taken of the existing standing waves, inside and outside the enclosure, without changing the distance from signal source to shield.



SS = Signal source

A_1 = Pick-up antenna location for measurement e_1 (should be point of maximum reading within distance d_2, but not closer than 2 inches from barrier)

A_2 = Pick-up antenna location for measurement e_2 (should be point of maximum reading)

B = Barrier (enclosure shield; single- or double-shield type)

$d_1 \geqslant 2\lambda$

$d_2 = \lambda/4$

d_3 = any distance for maximum reading inside enclosure, but not closer than 2 inches from barrier to prevent capacitive coupling

e_1 = First measurement

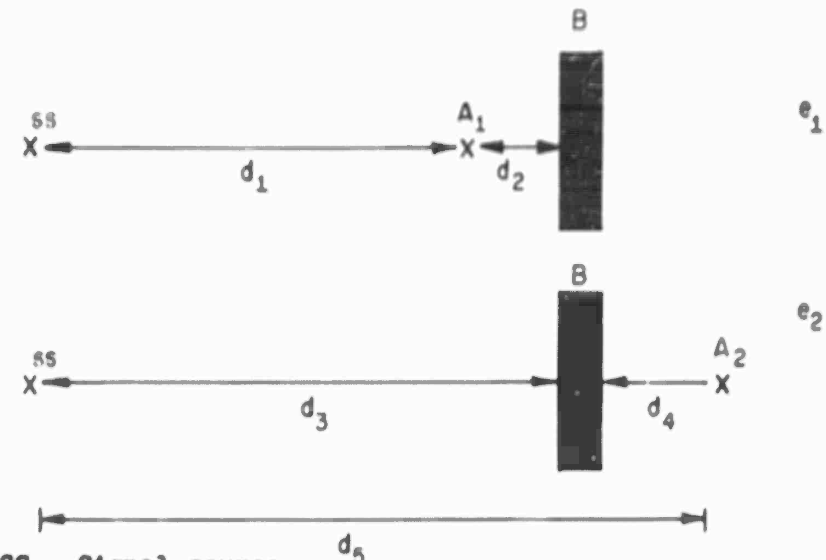
e_2 = Second measurement

FIGURE 6 - Modified Insertion-Loss Test - 20 to 1000 mc

"Attenuation" Test

Some investigators define shielding effectiveness as "attenuation" loss and measure it by taking the ratio (in db) of real powers, apparent powers, voltages, or currents on the outside and inside of the shielding enclosure. The test procedure is illustrated in figure 7. (Compare with insertion-loss test setup of figure 5.)

In the arrangement shown, d_1 is made much less than 1/6 of the wavelength $(\frac{\lambda}{2\pi})$ for electric fields and magnetic fields, and is made as large as possible (within power limits of the signal source) for plane waves. Distances d_2 and d_4 are not specified distances, but are usually made equal to each other and as short as possible. Distance d_3 is equal to d_1 plus d_2, since the same signal source-to-barrier distance is used in measurement steps e_1 and e_2. Therefore, distance d_5 is larger than d_1. The "attenuation" in db = $20 \log_{10} \frac{e_1}{e_2}$.



SS = Signal source

A_1 = Pick-up antenna location for measurement e_1

A_2 = Pick-up antenna location for measurement e_2

B = Barrier (enclosure shield; single-or double-shield type)

e_1 = First measurement

e_2 = Second measurement

NOTE: d_1 through d_5 represents respective distances shown

FIGURE 7 - "Attenuation" Test

This test method suffers from impedance changes and variations in signal strength at the measurement points caused by several uncontrolled variables in the test setup. In such a test, "attenuation" values will vary greatly for slight variations of some of the test-setup distances. Distance d_2, for example, is very critical and can greatly affect the impedance of the incident wave, for electric fields and magnetic fields, and can affect the strength of the received signal for all types of fields. A too short d_2 can change the characteristics of the pickup antenna and may introduce capacitive coupling between the antenna and the barrier. (These latter conditions also apply for distance d_4 which, as stated above, is made equal to d_2.) The presence of standing waves further emphasizes the critical nature of d_2. Under standing wave conditions, an arbitrarily-chosen distance for d_2 can produce either maximum or minimum readings in measurement step e_1. When these are compared with readings obtained in measurement step e_2, the ratio of the readings can indicate either a very high or very low "attenuation," neither of which represents the true effect produced by the barrier.

A major defect in the test setup concerns the increase in the distance from signal source to pickup antenna which results in going from measurement step e_1 to e_2. (See d_1 and d_5 of figure 7.) While the effect of the increase is not too serious in instances where d_1 is large, it is an important factor in instances where d_1 is relatively short, e.g., for electric fields and magnetic fields. Here the effect of the increase becomes noticeable and produces a measurable reduction in signal strength not assignable to the effect of the barrier.

From the foregoing, and from theoretical calculations based on transmission-line analogies, it is evident that this method is not adaptable for standardized testing calling for repeatable results. Furthermore, it can be shown that the "attenuation" obtained will vary depending upon whether ratios of real powers, apparent powers, voltages, or currents are being measured. For cases where the pickup antenna is relatively close to the barrier, these variations can be readily demonstrated by applying the equations of figure 4 as follows:

Real Power Ratio

Plane Waves -

$$\text{"Attenuation"} = 1/2 \left(20 \log_{10} \left| \frac{Z_1}{4\, Z_2} \right| \right) + A + 10 \log_{10} \left| \frac{\cos 45^\circ}{\cos 0^\circ} \right|$$

which is much lower than the insertion loss.

Electric Fields -

$$\text{"Attenuation"} = 1/2 \left(20 \log_{10} \left| \frac{Z_1}{4\, Z_2} \right| \right) + A + 10 \log_{10} \frac{\frac{\cos 45^\circ}{\beta^3 \gamma^3 - 2\beta\gamma}}{\sqrt{1 + \beta^6 \gamma^6}}$$

which can be much higher than the insertion loss.

Magnetic Fields -

$$\text{"Attenuation"} = 1/2 \left(20 \log_{10} \left| \frac{Z_1}{4\, Z_2} \right| \right) + A + 10 \log_{10} \left| \frac{\frac{\cos 45^\circ}{\beta^3 \gamma^3 - 2\beta\gamma}}{\sqrt{1 + \beta^6 \gamma^6}} \right|$$

which can be much higher than the insertion loss.

Apparent Power Ratio

$$\text{"Attenuation"} = 1/2 \left(20 \log_{10} \left| \frac{Z_1}{4\, Z_2} \right| \right) + A$$

which is much lower than the insertion loss.

Voltage Ratio

"Attenuation" = A - 6 db

which is much lower than the insertion loss.

Current Ratio

$$\text{"Attenuation"} = 20 \log_{10} \left| \frac{Z_1}{4 Z_2} \right| + A + 6 \text{ db}$$

which is of the same order as the insertion loss.

NOTE: For greater antenna-to-barrier distances, the mathematics becomes much more involved but the same variations in "attenuation" will be evident.

Surface Transfer Impedance Test

Some investigators advocate a surface transfer impedance test for determining shielding effectiveness. With this method, a constant r-f current is impressed on the inside surface of the shield-enclosure as the frequency is varied. The r-f voltage on the outside surface of the enclosure is then measured and the actual voltage measurement is taken as the surface transfer impedance and represents the shielding effectiveness of the metal, i.e., the lower the voltage the higher the shielding effectiveness. The surface transfer impedance method offers the following advantages:

1. Radiating and receiving antennas are not used.

2. Wave reflections are not present.

3. Wave impedance does not have to be considered.

4. All joints, seams, and discontinuities of the entire shielding enclosure are tested simultaneously.

Disadvantages of the surface transfer impedance method are as follows:

1. The method measures penetration loss only and does not evaluate the amount of reflection loss present at the outside and inside surfaces of the enclosure. Although penetration loss is generally the major factor in shielding effectiveness, it is not the major factor for instances where the enclosure shields are "electrically thin," or for frequencies below 1 mc. For example, the penetration loss provided by 10-mil copper sheet at 150 kc is 12.9 db as compared with its total reflection loss of 176.8 db for electric fields, 117.0 db for plane waves, and 56.0 db for magnetic fields.

2. Measurements of surface transfer impedance cannot be expressed in db unless measured values are referred to a standard shielding material.

3. The method cannot be used readily above 10 mc because of the difficulty of obtaining sufficiently high r-f currents at the higher frequencies.

4. The method places the signal source inside the enclosure and the measuring equipment outside. The measurement of low r-f voltages on the outside of a shielded enclosure is frequently hampered by the presence of unavoidable high ambient interference.

SECTION II

SHIELDED ENCLOSURE DESIGNS AND NADC-AEEL TAKEDOWN CELL-TYPE SCREEN ROOM

ENCLOSURE DESIGNS

In general, shielded enclosure designs fall into two categories: the permanently-constructed non-takedown type, and the takedown type. Both types are adaptable to either single- or double-shield construction and double-shield takedown types can be built using either cell-type or isolated-shield type construction. For practical reasons, the cell-type takedown enclosure is currently favored and is available commercially from numerous suppliers.

Non-Takedown Type Enclosures

The non-takedown type of shielded enclosure is comprised of a permanently-constructed complete wood framework to which is attached metal sheets or screening material. The enclosure thus formed is an integral unit with the wood members nailed, dowelled, or screwed together and with the metal sheathing soldered or welded at the seams and joints. The initial cost of non-takedown enclosures may be lower than that for the takedown types, but the saving in cost is frequently nullified by early obsolescence. Objections to the non-takedown type enclosures are as follows:

1. Non-takedown enclosures cannot be taken apart successfully for relocation or storage. Attempts to dismantle enclosures of this type generally result in irreparable damage to the over-all structure, whether the enclosure is taken apart in large sections or is reduced to its original component parts. Dismantling of these enclosures for material salvage is usually not worth the labor cost involved. For these reasons, non-takedown enclosures are often abandoned after their initial purpose has been served and perform no further service except, possibly, as material storage compartments. Many plants and laboratories have several such "dead soldiers" on hand.

2. The construction of non-takedown enclosures does not lend itself to commercial production and transportation methods, and manufacturers have expressed little interest in this type of equipment. Non-takedown enclosures are therefore constructed right in the plant or laboratory areas where they are to be used. In many instances they are built by personnel (carpenters, sheet-metal workers, maintenance men, etc.) unacquainted with the particular constructional demands of the shielding art. For these reasons there has been little standardization of design and construction for this type of enclosure and specification requirements have never been coordinated.

3. The soldering or welding of the seams of non-takedown enclosures is a critical operation which must be performed by skilled personnel. A good solder joint, for example, can produce a perfectly adequate low r-f impedance bond for shielded enclosure work, but a poor joint (which may not be detectable by cursory visual inspection) can constitute a serious discontinuity in the enclosure shield and greatly reduce shielding effectiveness. If acid- or salt-content flux (flux of this type should never be used in shielded enclosure work) has been used in the soldering operation, corrosion will result and the joint will deteriorate with age. A clean metal-to-metal contact under adequate pressure, such as is used for panel joints of takedown type enclosures, can produce a much lower r-f impedance bond than a poor solder connection. (See reference (n).)

4. Maintenance and repair work on non-takedown enclosures is often made all but impossible because of the inaccessibility of the areas affected. Deterioration with age is therefore much more of a factor for non-takedown enclosures than for the takedown types. Similarly, the correction of post-construction defects is largely precluded. (See reference (o) for a typical instance where enclosure defects developed after completion of construction.) Modification of completed enclosures is also extremely difficult.

Takedown Type Enclosures

Almost all takedown* types of shielded enclosures and screen rooms are made up of individual prefabricated panels which are bolted together to form the floor, walls, and ceiling. A door and doorframe panel is also included. The individual panels generally take the form of a braced rectangular frame covered with copper screening material or sheet metal. The basic panel design lends itself readily to single- or double-shield construction and the latter type can be adapted to either isolated-shield or cell-type arrangements.

Wood is the usual material for the panel frames. In panel fabrication the shielding material is folded over the edges of the frame periphery and metal-to-metal contact between the prefabricated panels is achieved when panel edges are bolted together to assemble the enclosure. The inherent resiliency of the panel wood framework makes for efficient bolting-pressure distribution and misalignment takeup at joints between panels and contributes greatly to the achieving of low r-f impedance bonds between the enclosure components. Panels with metal frames have proved unsatisfactory thus far.

The takedown type of shielded enclosure possesses the following advantages which just about remove all the objections raised for the non-takedown type.

1. Takedown enclosures can be assembled or disassembled as the occasion demands, with little or no deterioration of the enclosure component panels. Enclosure components can be transported or stored readily and storage and transportation space requirements are relatively small. Consequently, takedown enclosures do not have to be discarded when laboratory or plant facilities are changed or moved.

2. Takedown enclosure production is readily adaptable to commercial fabrication and shipping procedures. The presently-accepted basic design includes numerous standardized features, as regards construction details and materials, and has stimulated considerable interest and development work on the part of manufacturing concerns. At least seven manufacturers of screen rooms and enclosures have been established since 1947. NADEVCEN was instrumental in establishing Specification No. MIL-S-4957(Aer), reference (p), for use in the procurement of large numbers of shielded enclosures. The specification is based on the design and construction details of the NADC-AEEL Takedown, Cell-Type Screen Room and over 1000 enclosures of this type have been manufactured and sold in the last 4 years.

3. Takedown enclosures can be assembled or disassembled quickly by relatively untrained personnel. Enclosures of this type can be disassembled and reassembled in another location in one day's time by two workmen.

---

* The term takedown is used to indicate the assembly and disassembly feature of this type of enclosure. Takedown enclosures are only portable in a knocked-down form.

4. Inspection, repair, and maintenance operations are greatly facilitated by the paneled construction of takedown enclosures. If necessary, a panel can be removed from an assembled enclosure to a workbench for repair operations and a severely damaged panel can be replaced with a duplicate procured from the enclosure manufacturer. All panel joints are readily accessible for inspection and cleaning. Test experience has shown that panel joints should not require cleaning more than once every 3 years. (The first screen room produced in accordance with the NADC-AEEL takedown, cell-type design is still in use and its shielding effectiveness has decreased less than 4 db in 7 years of continuous service.)

5. Takedown enclosures offer many possibilities for new designs and allow for modifications of existing designs. This enables existing models to be brought up to date by the addition or substitution of improved or newly-developed fittings and materials and permits changes in basic designs for special purpose applications.

6. The length dimension of a takedown enclosure is variable and the enclosure can be made longer or shorter by the simple expedient of adding or subtracting the proper number of floor, wall, and ceiling panels.

7. Takedown enclosures of cell-type construction permit the ready entrance of various services such as gas, water, and air lines, forced-air ventilation ducts, rotating-shaft motive power, etc.

8. The higher initial cost of takedown enclosures is more than compensated for by their long service life, functional versatility, and low maintenance costs.

Cell-Type Versus Isolated-Shield Construction

Although the shielding effectiveness of isolated-shield type takedown enclosures is slightly superior to that of cell-type enclosures for certain fields and frequencies, the latter type has become the accepted standard because of numerous construction advantages. These include the following:

1. Half the number of electrical joints are involved and the metal-to-metal contact areas are nearly doubled.

2. Half as much wood framework material and half as much panel-mounting hardware (bolts, nuts, and pressure plates) are required; panel weight also is halved.

3. Panel fabrication costs (material and labor) are reduced considerably.

4. Panel fabrication time and enclosure erection time are greatly reduced.

5. Less maintenance and repair work is required and much less work time is involved.

Cell-type construction can best be explained by a description of the basic construction of one component panel of a cell-type screen room. Each such panel is essentially a thin, box-like, 6-sided screened cell some 7 or more feet long, 30 or more inches wide, and 1 inch thick. (The 1-inch dimension is exclusive of the exposed wood frame-work.)

In fabricating a cell-type panel two rectangular, braced, wood frames (similar in appearance to full-length window screen frames) are constructed of seasoned pine lumber,

one of 1- by 2-inch material and the other of 1- by 1-inch material. Each frame is faced on one side with copper screening, the length and width dimensions of which are several inches larger than the frame. The screening is attached to the frames by tacks (or wood screws), the heads of which are electrically bonded to the screen material by soldering. The two frames are next permanently fastened together with the screened surface of one in contact with the wood framework surface of the other. The composite panel frame thus formed has one outside screened surface, an inner screened surface (sandwiched in between the two frames) and a final outside surface of exposed wood framework. This exposed wood framework contains holes for bolting panels together to form the room.

In the final stage of panel fabrication, the protruding edges of the two screen layers are folded over in a 2-ply overlap on the panel frame periphery and tacked down. This operation transforms the 2-screen panel into a 6-sided screened cell. Because of the 2-ply overlap on all edges of the periphery of each individual panel, 4 layers of screening are actually placed in contact under pressure wherever panels are joined in the assembly of the screen room. This makes for efficient low r-f impedance bonds between the room's component "cells." The dimensions of the two wood-frame components of the composite panel frames are such that the final edges of the completed panels are stepped and thus a mortised joint is achieved wherever adjacent panels meet perpendicularly. This feature adds greatly to the strength and rigidity of the assembled screen room and provides flush panel joints for interior room surfaces.

NADC-AEEL TAKEDOWN CELL-TYPE SCREEN ROOM

The NADC-AEEL Takedown Cell-Type Screen Room is a double-shield, cell-type enclosure using 22-mesh, 15-mil, copper screening; with a nominal 1-inch spacing between inner and outer shields (screens). The room provides a nominal 100 db of shielding effectiveness over a frequency range from 0.15 to 10,000 mc. (See figure 8.) The standard model is assembled from 30 prefabricated panels which form the floor, walls, and ceiling. An r-f leakproof door and doorframe assembly constitutes one of the panels. The room design includes plywood flooring panels as an overlay for the screened floor panels. The outside dimensions of the standard size room are: 8 feet 2 inches wide by 7 feet 4 inches high by 16 feet long. The length of the room can be varied by adding or subtracting the proper number of floor, wall, and ceiling panels.

A diagrammatic sketch illustrating the room's panel and screening arrangement is given in figure 9.

Figure 10 presents detailed engineering drawings and a bill of materials.

Views of the room and its components are shown in figures 11 through 16.

Additional views and screen room erection and maintenance information are presented in the appendix.

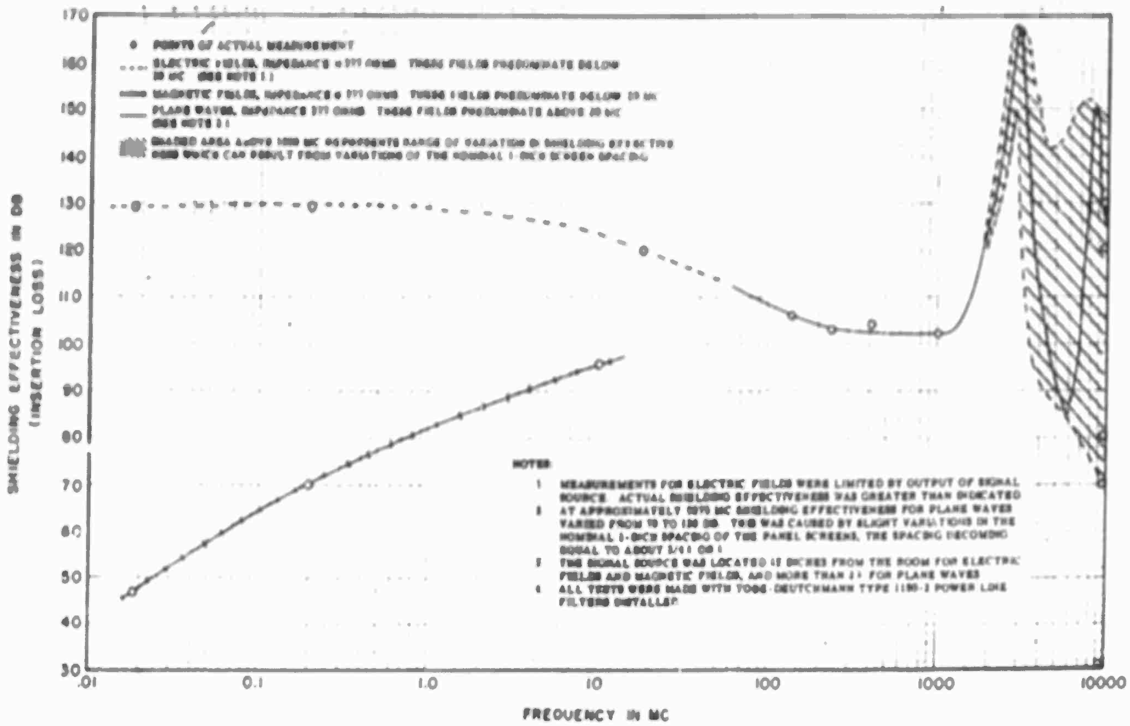
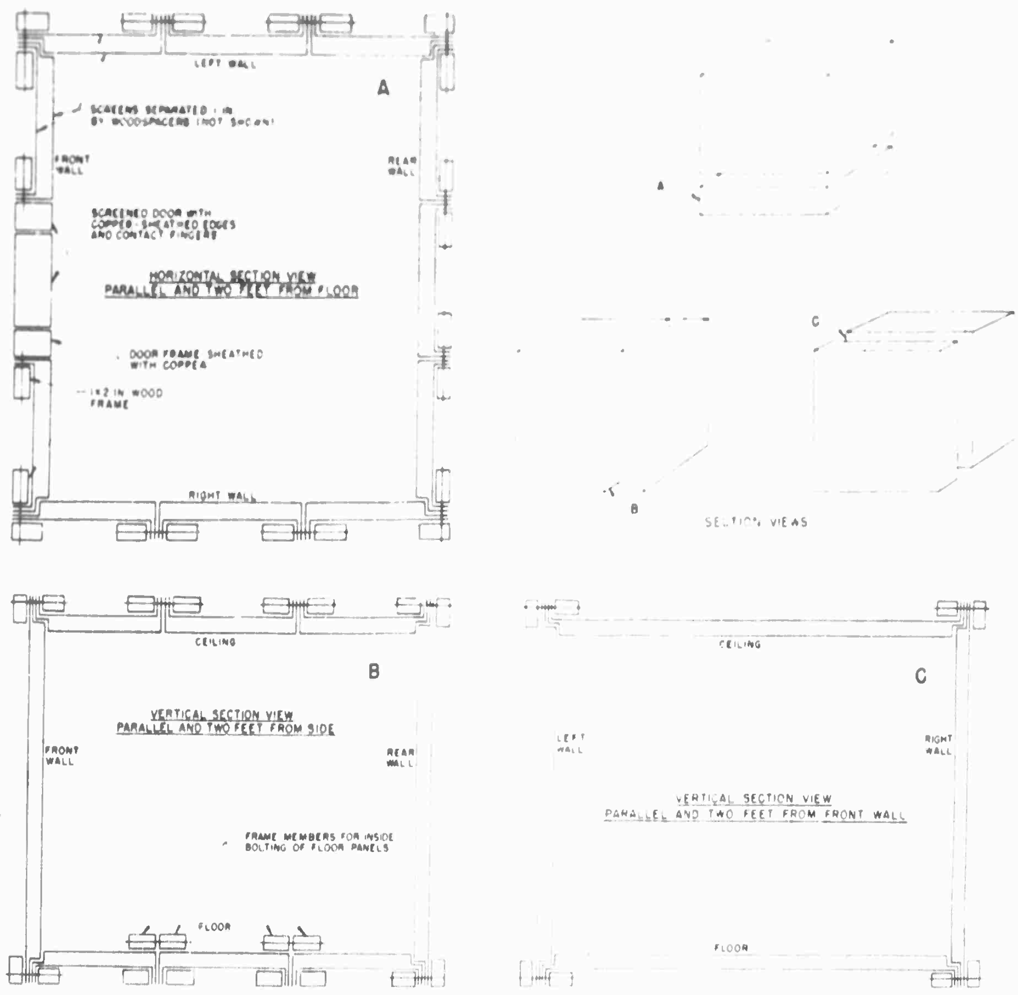


FIGURE 8 - Typical Shielding Effectiveness of NADC-AEEL Takedown Cell-Type Screen Room



IGURE 9 - Diagrammatic Sketch Illustrating Panel and Screening Arrangement of NADC-AEEL Takedown Cell-Type Screen Room

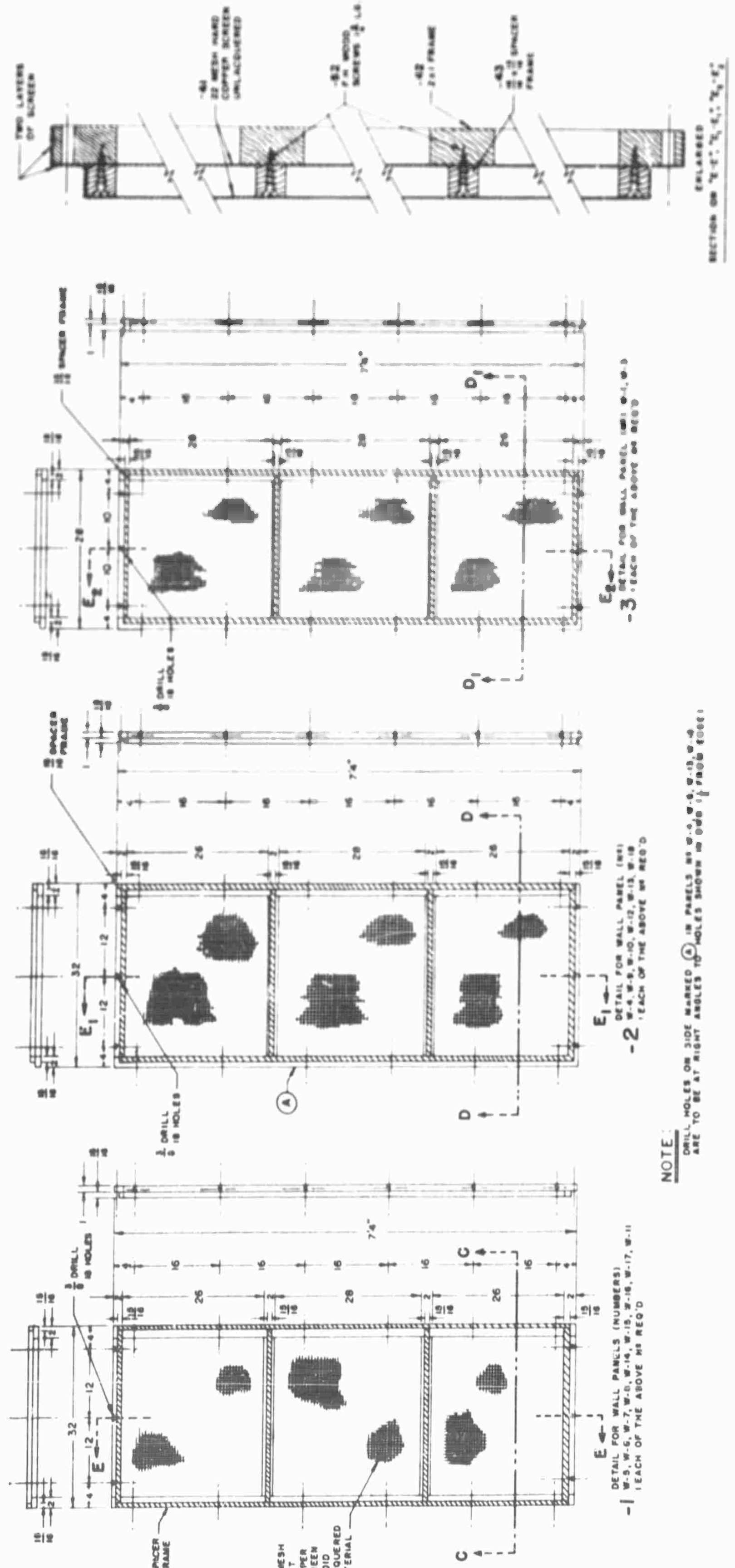


FIGURE 10 - NADC-AEEL Takedown Cell-Type Screen (from NADC Drawing No. E-1001)

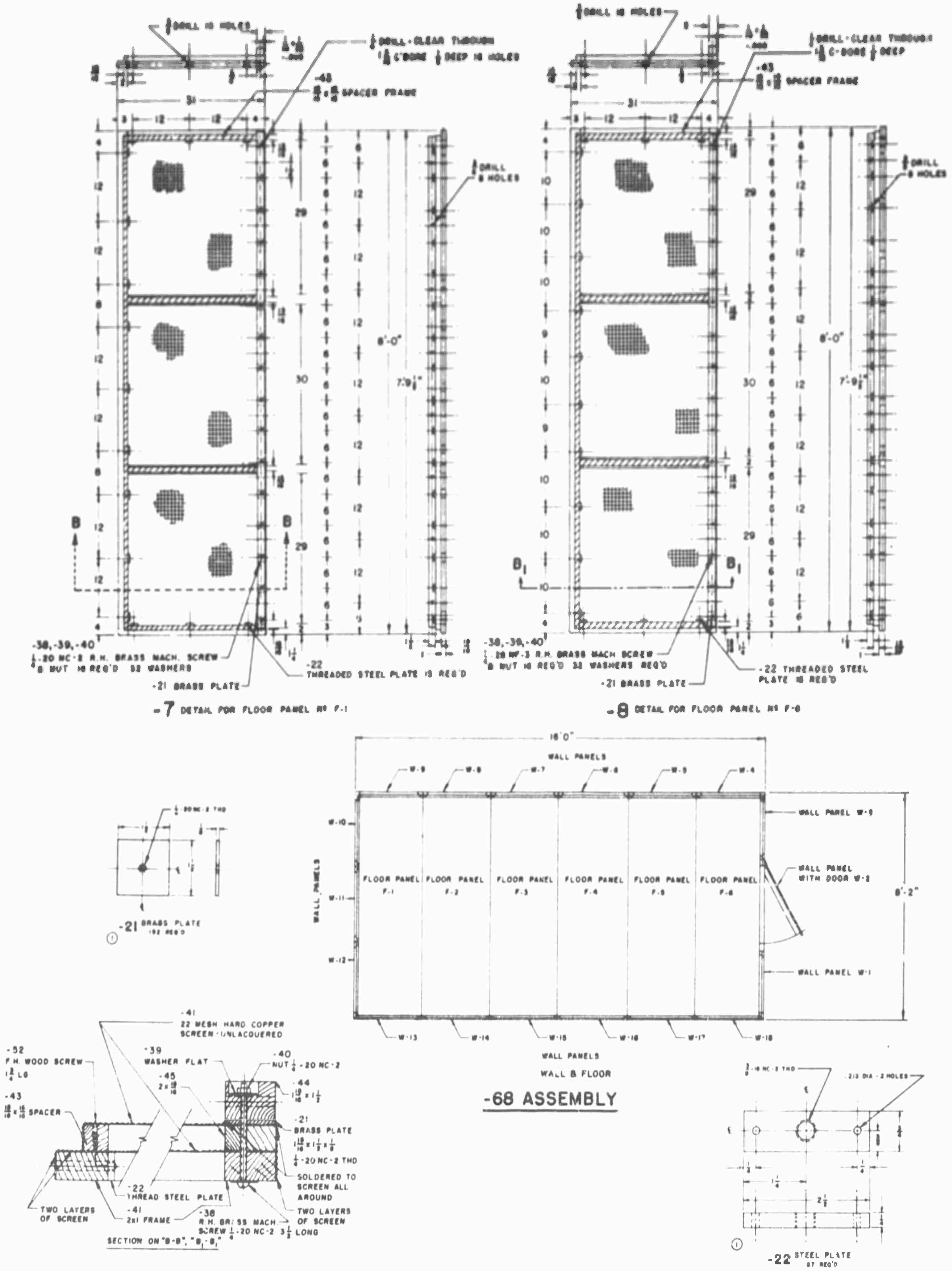


FIGURE 10 (continued)

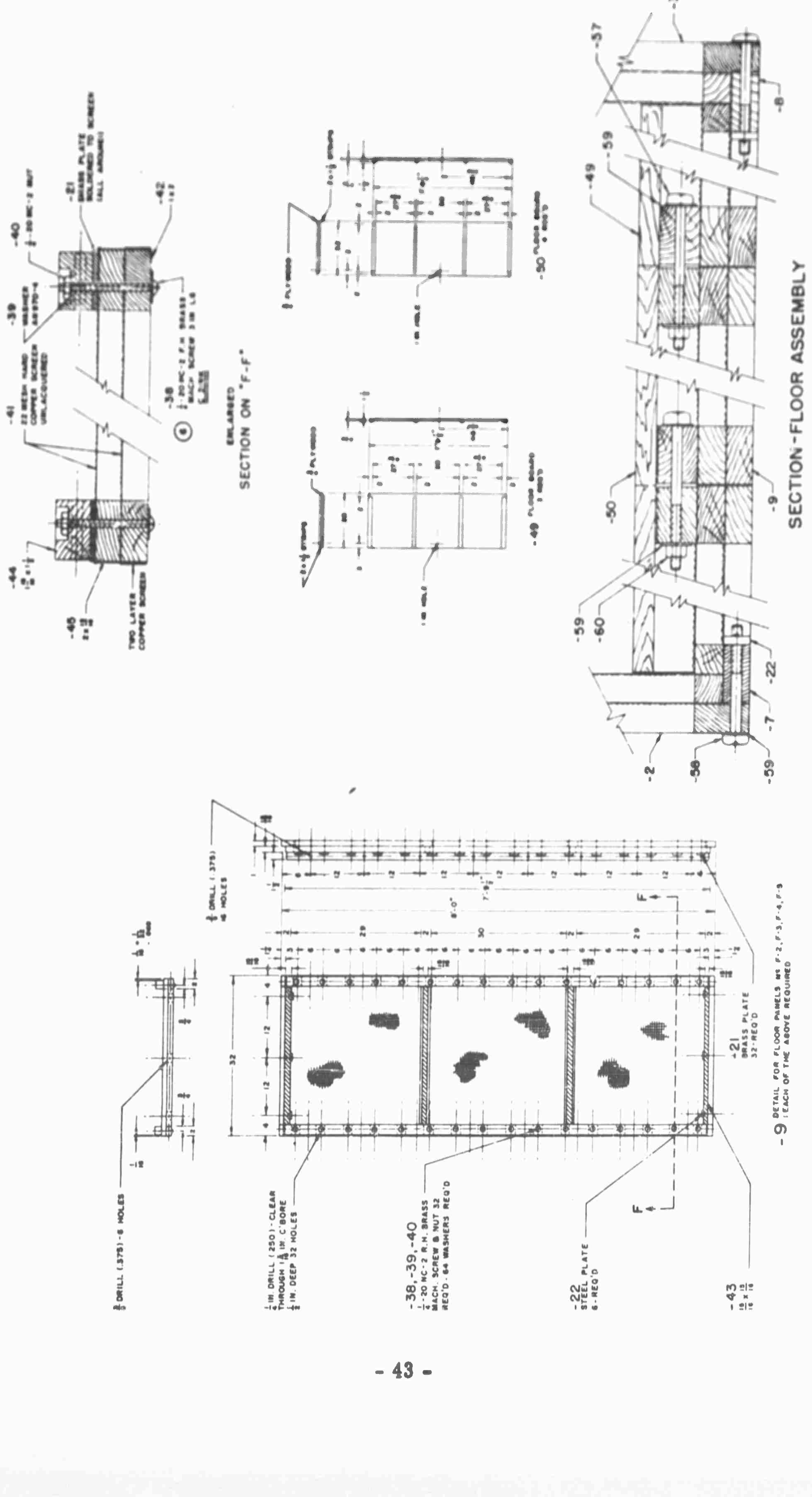


FIGURE 10 (continued)

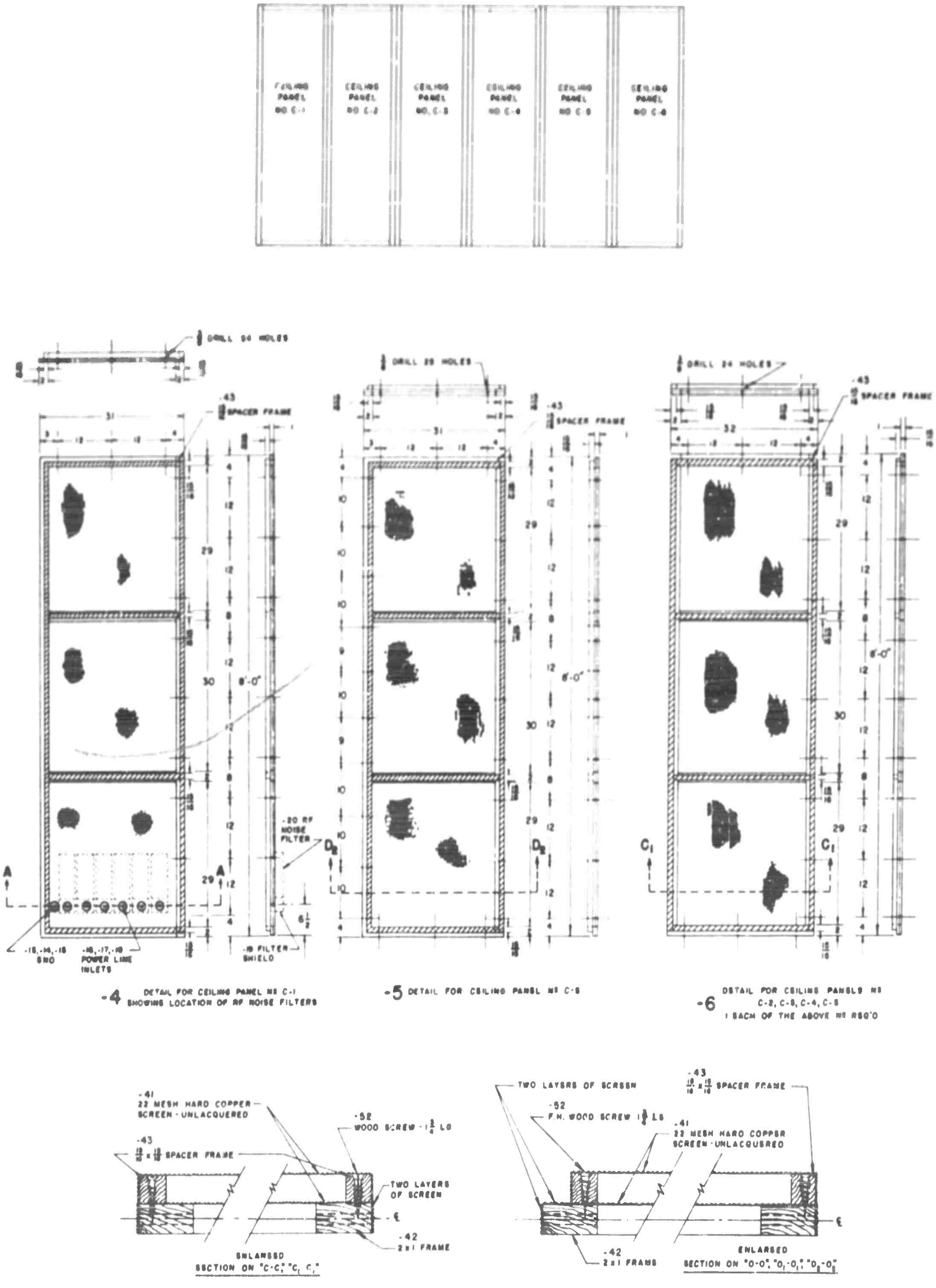


FIGURE 10 (continued)

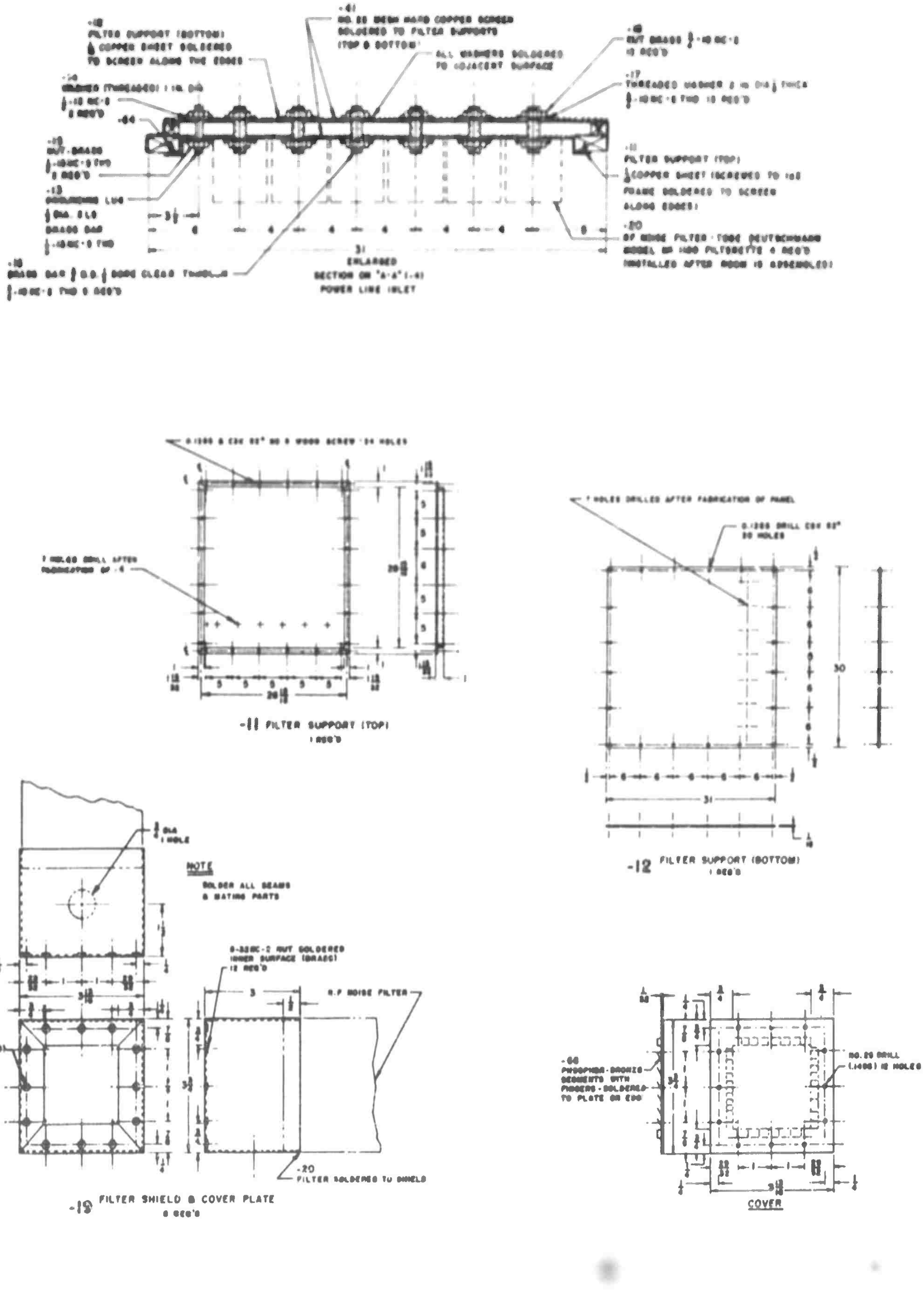


FIGURE 10 (continued)

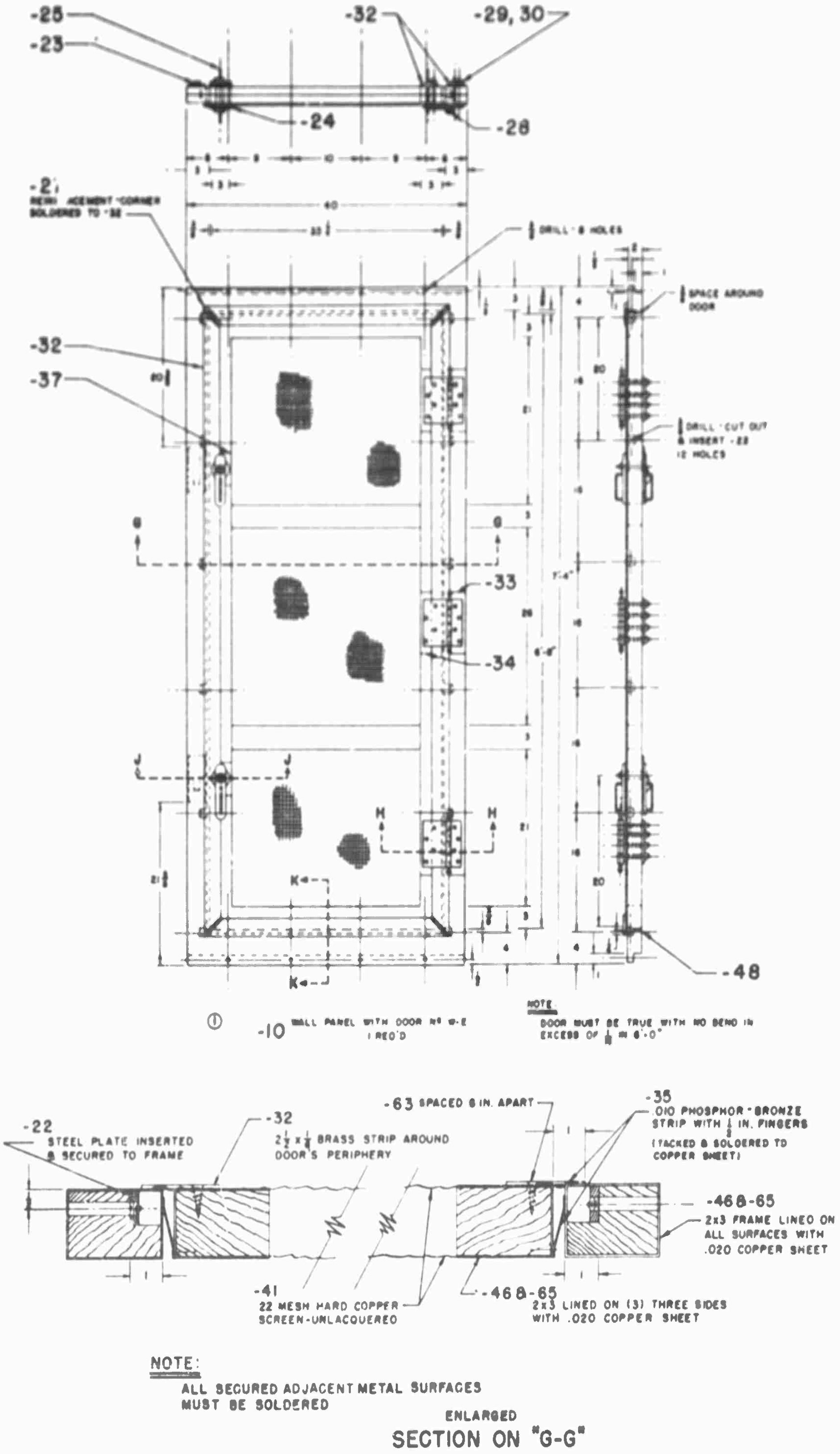


FIGURE 10 (continued)

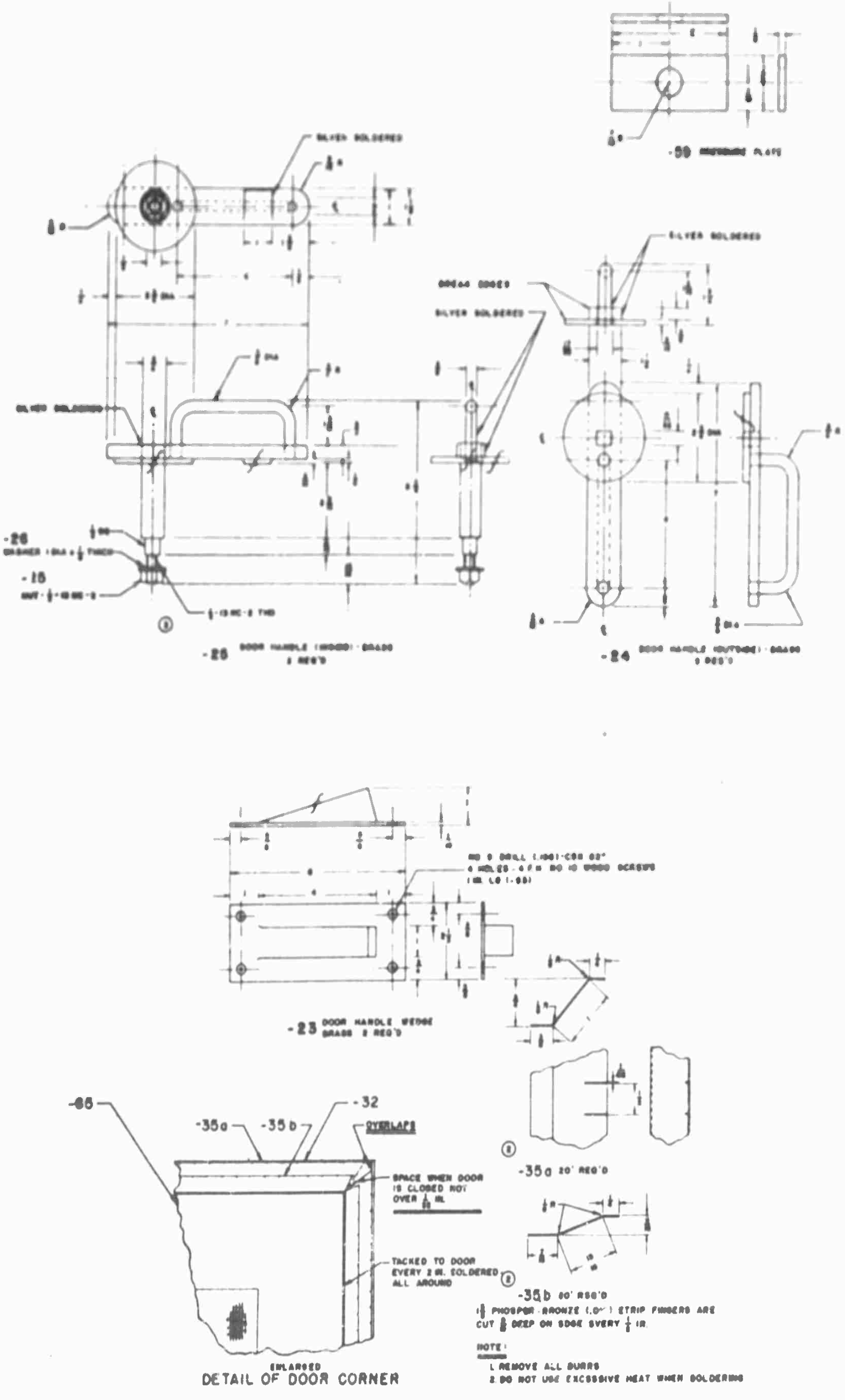


FIGURE 10 (continued)

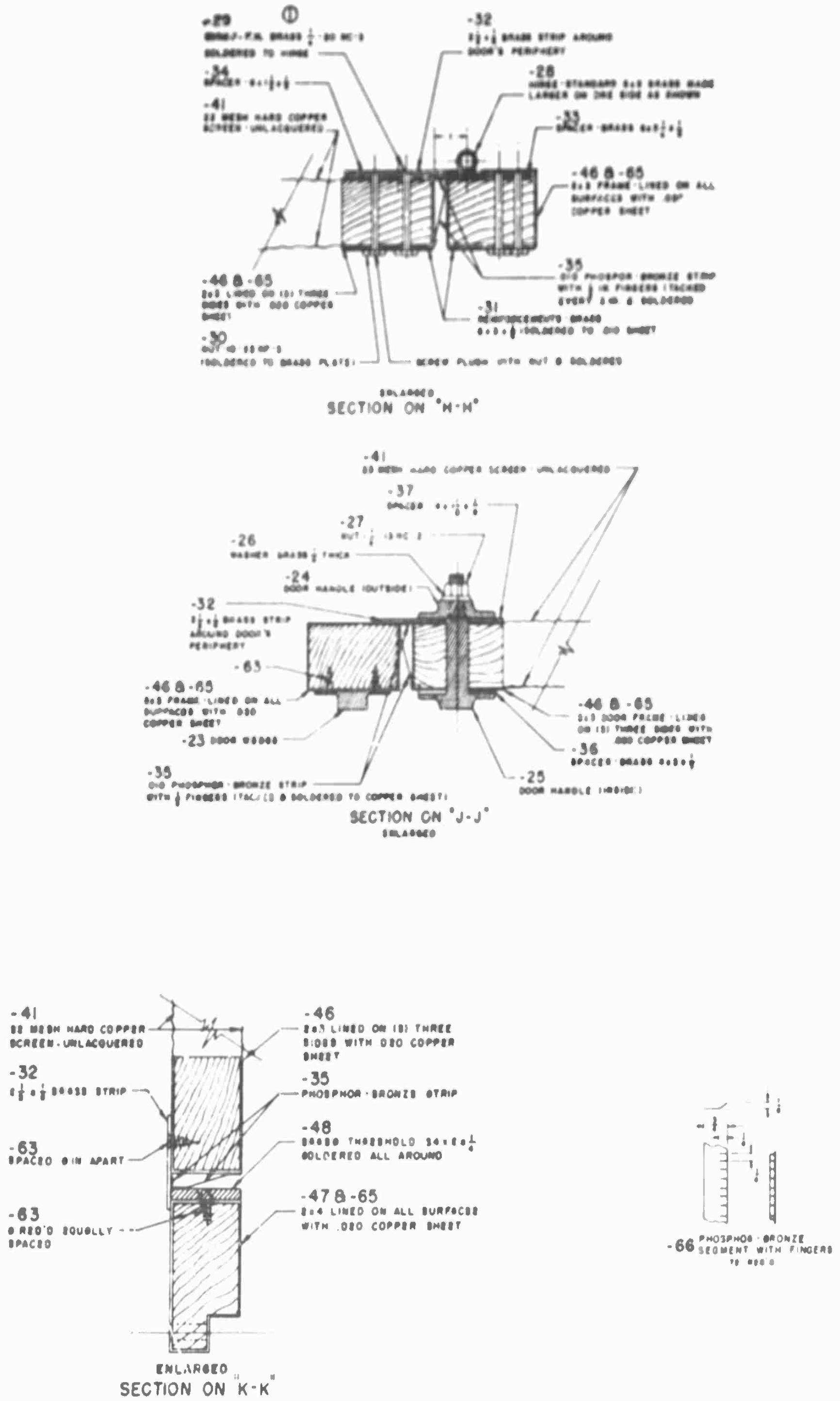


FIGURE 10 (continued)

BILL OF MATERIALS FOR NADC DRAWING NO. E-1001

No. Per Assem.	Part No.	Part Name	Stock	Material	Remarks
9	-1	Wall Panel			
6	-2	Wall Panel			
2	-3	Wall Panel			
1	-4	Ceiling Panel			
1	-5	Ceiling Panel			
4	-6	Ceiling Panel			
1	-7	Floor Panel			
1	-8	Floor Panel			
4	-9	Floor Panel			
1	-10	Wall Panel with Door			
1	-11	Filter Support	31 x 30 x 1/16 in.	Copper	Spec. No. QQ-C-501, Class "A"
1	-12	Filter Support	31 x 30 x 1/16 in.	Copper	Spec. No. QQ-C-501, Class "A"
1	-13	Grounding Lug	1/2 x 5 in. Rod	Brass	Commercial Standard
2	-14	Threaded Washer	1 in. dia x 1/8 in.	Brass	Commercial Standard
2	-15	Nut-1/2"-13 NC-2	Standard	Brass	Commercial Standard
8	-16	Power Inlet	3/4 in. OD x 3 in. lg	Brass	Commercial Standard
12	-17	Threaded Washer	2 in. dia x 1/8 in.	Brass	Commercial Standard
2	-18	Nut-3/4"-10 NC-2	Standard	Brass	Commercial Standard
6	-19	Filter Shield	1/32 in. Sheet	Copper	Spec. No. QQ-C-501, Class "A"
4	-20	Filter			See Note No. 16
192	-21	Plate	0.125 x 1-1/2 x 1-1/2 in.	Brass	
67	-22	Plate Nut	1/4 x 3/4 x 2-1/2 in.	Steel	Spec. No. AN-QQ-S-689
2	-23	Door Handle Wedge		Brass	Commercial Standard
2	-24	Door Handle		Brass	Commercial Standard
2	-25	Door Handle		Brass	Commercial Standard
2	-26	Washer	1 in. dia x 1/8 in.	Brass	Commercial Standard
4	-27	Reinforcement	4 x 1 x 1/8 in.	Brass	Commercial Standard
3	-28	Hinge	Standard	Brass	See Note No. 9
24	-29	F.H. Machine Screw	1/4-20 NC-2 x 2-1/2 in.	Brass	Commercial Standard
24	-30	Nut-10-32	AN345B10	Brass	Commercial Standard
6	-31	Reinforcements	6 x 3 x 1/16 in.	Brass	Commercial Standard
	-32	Strip	20 ft x 2-1/2 in. x 1/8 in.	Brass	Commercial Standard
3	-33	Spacer	6 x 2-1/8 x 1/8 in.	Brass	Commercial Standard
3	-34	Spacer	6 x 1-1/2 x 1/8 in.	Brass	Commercial Standard
	-35	Strip	0.010 x 1-5/8 in. x 40 ft	Phosphor-Bronze	Spec. No. QQ-B-746
2	-36	Spacer	4 x 2 x 1/8 in.	Brass	Commercial Standard
2	-37	Spacer	4 x 1-1/2 x 1/8 in.	Brass	Commercial Standard
192	-38	F.H. Machine Screw	1/4-20 NC-2 x 3 in.	Brass	
200	-39	Washer	AN 970-4		
192	-40	Nut-1/4-20	AN340B416		
1368 sq ft	-41	Copper Screening			See Note No. 3
688 ft	-42	Wood	1 x 2 in.		See Note No. 1
583 ft	-43	Wood	15/16 x 15/16 in.		See Note No. 1
10	-44	Wood	1-15/16 x 1-1/2 in. x 7 ft 9-1/2 in.		See Note No. 1
157 ft	-45	Wood	2 x 15/16 in.		See Note No. 1
34 ft	-46	Wood	2 x 3 in.		See Note No. 1
1	-47	Wood	40 x 4 x 2 in.		See Note No. 1
1	-48	Threshold	34 x 2 x 1/4 in.	Brass	Commercial Standard
2	-49	Floor Board	7 ft-9-1/2 in. x 30 in. x 3/4 in.	Plywood	
4	-50	Floor Board	7 ft-9-1/2 in. x 32 in. x 3/4 in.	Plywood	
	-51	Copper Tacks	Standard No. 8	Copper	See Notes No. 3 and 5
	-52	F.H. Wood Screw	AN550B10-14		See Note No. 4
44	-53	F.H. Wood Screw	AN550B5-4		See Note No. 7
114	-54	R.H. Wood Screw	AN545-10-6		
117	-55	Sq. Hd. Bolt	3/8-16 x 4-1/2 in.		
79	-56	Sq. Hd. Bolt	3/8-16 x 3-1/2 in.		
55	-57	Sq. Hd. Bolt	3/8-16 x 4-1/2 in.		
52	-58	Sq. Hd. Bolt	3/8-16 x 3-1/2 in.		
575	-59	Washer	1/8 x 7/8 x 2 in.	Steel	Spec.No. AN-QQ-S-689
303	-60	Nut 3/8-16	AN340-616		
12	-61	R.H. Machine Screw	8-32 x 1/4 in.	Brass	Commercial Standard
12	-62	Nut 8-32	AN340B10	Brass	
54	-63	F.H. Wood Screw	AN550B10-8	Brass	See Note No. 7
44	-64	F.H. Wood Screw	AN550B5-6	Brass	
40 sq ft	-65	0.020 Sheet	(minimum lg = 9 ft)	Copper	Spec.No. QQ-C-501, Class "A"
	-66	Segment Strip	0.010 x 3/4 x 72 in.	Phosphor-Bronze	Spec.No. QQ-B-746
	-67	Wood	1/2 x 2 inches x 440 ft		See Note No. 12

Bill of Materials for Figure 10

NOTES FOR NADC DRAWING NO. E-1001

1. Use dressed, well seasoned white pine or aircraft spruce for frames of floor, wall, and ceiling panels; use first grade maple for door and doorframe of wall panel with door.

2. Use mortise and tenon joints in constructing door and doorframe of wall panel with door. Frames of floor, wall, and ceiling panels shall be dowelled.

3. Panel screening shall be 22-mesh copper fabricated from unlacquered 26-guage (0.0159 in. dia) hard drawn wire. Screening is separately applied to panel frame sections before they are permanently fastened together to form complete panels. Screening may be secured to the face of section frames with copper tacks. Final edges of screens are folded over and tacked to the edges of the periphery of the composite frame formed by the joining of the two screened sections; screening for the sections must be cut large enough to provide the fold-over areas. (See dwg enlarged detail sections "B-B," "C-C," "C_1-C_1," "D-D", "D_1-D_1," "D_2-D_2," "E-E," "E_1-E_1," "E_2-E_2.") It should be noted that folded screen areas of the spacer section partially overlap folded areas of the main section and dimensions of the screening cut for the spacer section must provide for the greater depth of fold.

4. The two screened sections comprising a panel shall be screwed together with No. 10 flat head wood screws 1-3/4 in. lg as indicated. Screws shall be spaced 4 in. apart.

5. No. 8 copper tacks shall be used to attach screening to frames.

6. Fold-over areas of section screens shall be notched at corners to permit forming of corners on panel frame periphery; notches shall be so cut as to allow 1/8-in. overlap which shall be soldered.

7. All exposed heads of tacks and wood screws shall be soldered to screens (heads of tacks and wood screws used in attaching copper sheathing, brass strips, and phosphor bronze contact strips to door and doorframe also shall be soldered). In general, all mechanically secured joints of a permanent nature on panels and door and doorframe shall be soldered. All exposed cut edges of screens shall be soldered (and wiped clean) to prevent fraying. Holes provided in screens to accommodate 3/8-in. dia panel mounting bolts also shall have edges soldered.

8. Solder should have at least 50% tin content and should have resin core. If additional flux is necessary, use alcohol and resin mixture; no acid pastes or soldering salts shall be used. Soldered surfaces shall be buffed to remove resin residue.

9. Door hinges are standard brass 5-in. loose-pin type with extension plate welded to one half.

10. The 1/4-in. portion of the serrated phosphor bronze strips (dwg detail No. 35a and 35b) shall have a very slight overall curvature to form the contact fingers. In performing the bending operation, a round-edge tool of the proper radius shall be used. When completed door is hung and is in the closed position, all contact fingers shall make good contact with the doorframe. Contact fingers shall be free of burrs and shall be buffed.

11. Completed panels shall be permanently marked for identification purposes as shown in assembly detail. Identifying letters and numerals should be at least 1/2-in. high and be so placed as to be readily visible during assembly and disassembly of the room.

12. Wood strips of 1/2 by 2-in. stock should be attached horizontally to the outside of the wall panels to protect panel screens. Strips should be spaced 2 in. apart and should extend from the floor to a height of approximately 3 ft.

13. After completion of the room components, the room should be assembled to insure that all parts are mating properly. Panels should be bolted together using square head 3/8-in. dia bolts and hex nuts. A pressure distributing plate ("washer," part No. -59) shall be used under bolt heads and under nuts.

NOTE: Where room is to be assembled for extended period, lockwashers should be used between nuts and pressure plates. Joints between mating panels of completed room should be tight and present no visible interstices. Correct bolt tightening pressure is 140 in-lb and should be checked with a torque wrench.

14. A sign (2 by 18 by 1/4 in. Masonite) bearing the following legend shall be fastened to both sides of the screen room door:

CLOSE DOOR SLOWLY
DO NOT SLAM!

15. A sign (2 by 18 by 1/4 in. Masonite) bearing the following legend shall be installed on room side of screen room door:

FOR ASSEMBLY AND MAINTENANCE
REFER TO
BUAER PROJECT NO. ADC EL-538
AND
REPORT NO. NADC-EL-54129

16. Screen room power line filter should be Tobe Deutchmann Corp. model No. 1180 Filterette, or equivalent, with rating of 100 amp, 500 V ac/dc; total capacity 7.0 uf. Filterette attenuation (conducted) is as follows:

60 db from 0.15 to 0.4 mc
80 db from 0.4 to 1.0 mc
106 db from 1.0 to 50 mc
86 db from 50 to 400 mc

If substitute filter is used, unit shall provide equal attenuation or better.

17. With power lines connected, assembled screen room shall provide nominal shielding effectiveness of 100 db for the frequency range of 0.15 to 150 mc.

18. Construction or material deviations may render screen room ineffective; deviations should be made only after careful consideration and should be authorized by consulting engineer versed in the shielding art.

19. With 32-in. wide panels as indicated in the drawings, the overall inside dimensions of the room using 6 sections will be

Width - 7 ft 3-in.
Length- 15 ft 8-in.
Height- 7 ft 0-in.

The panel width may be changed from 32-in. to 40-in. without changing the overall design. In this case the room will be somewhat larger and the door can be installed in any one of the wall sides.

Fabrication Notes for Figure 10

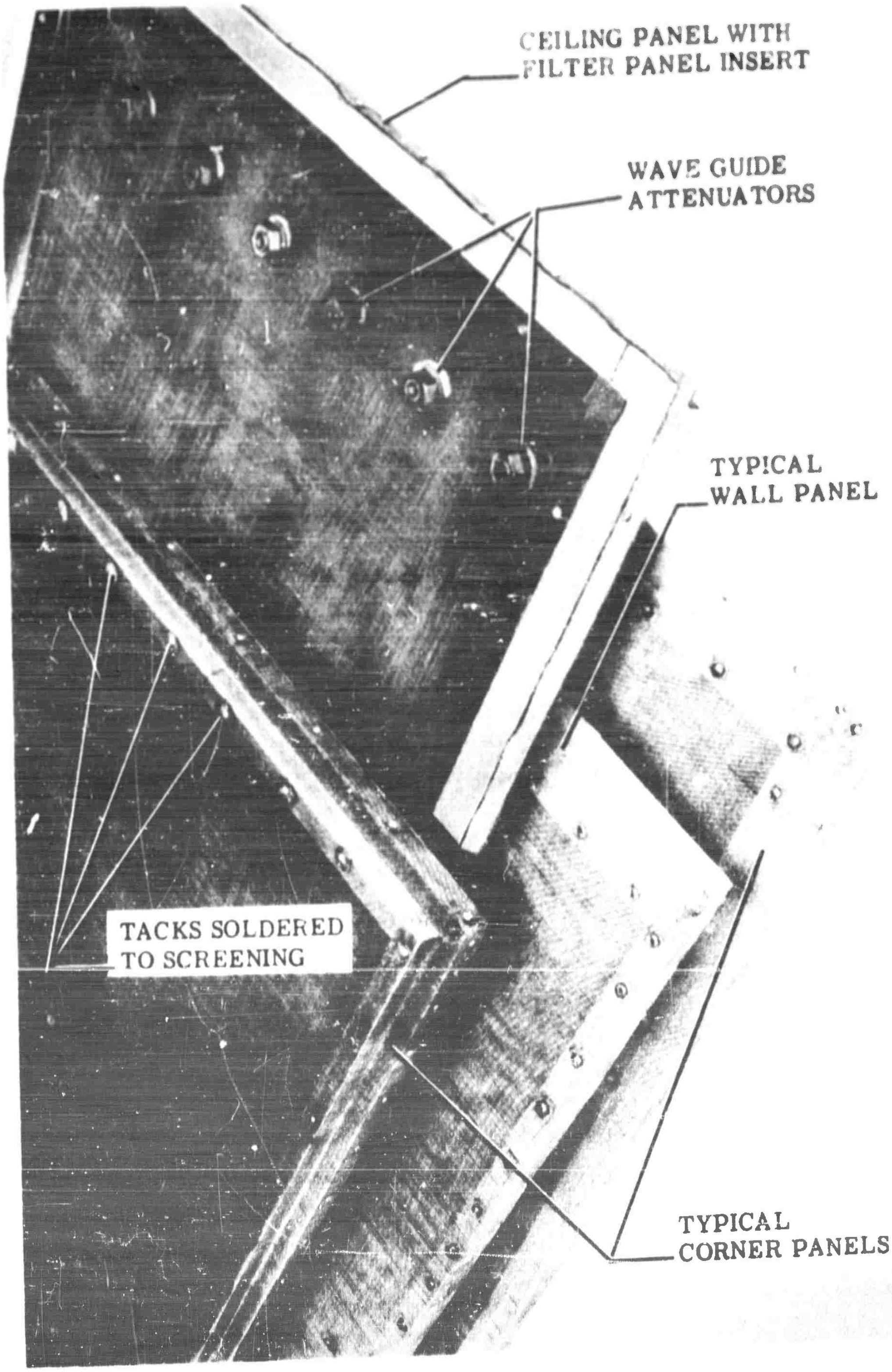


FIGURE 11 - Fabricated Screen Room Panels Showing Periphery Details

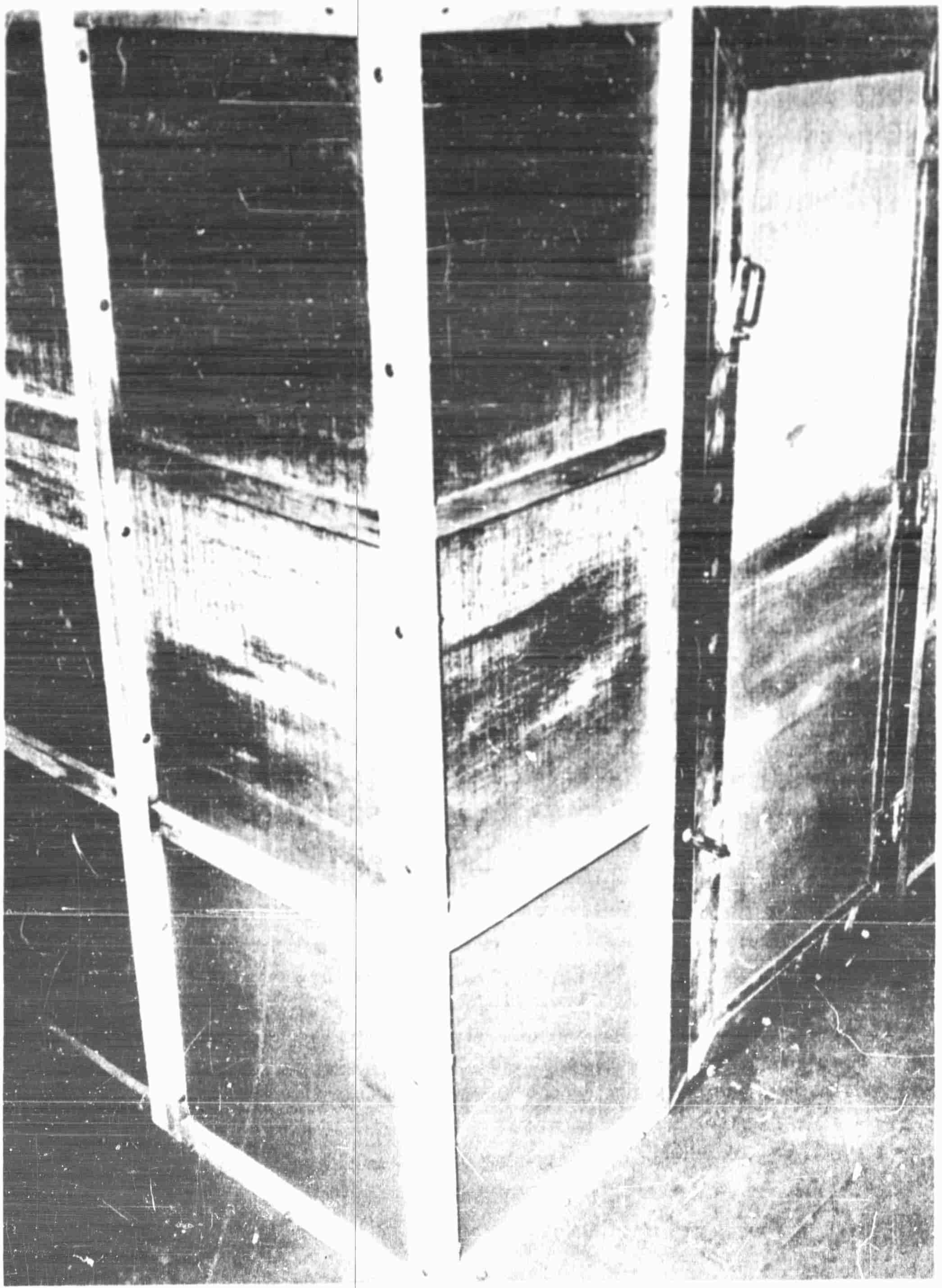


FIGURE 12 - Corner View of Exterior of Assembled Screen Room

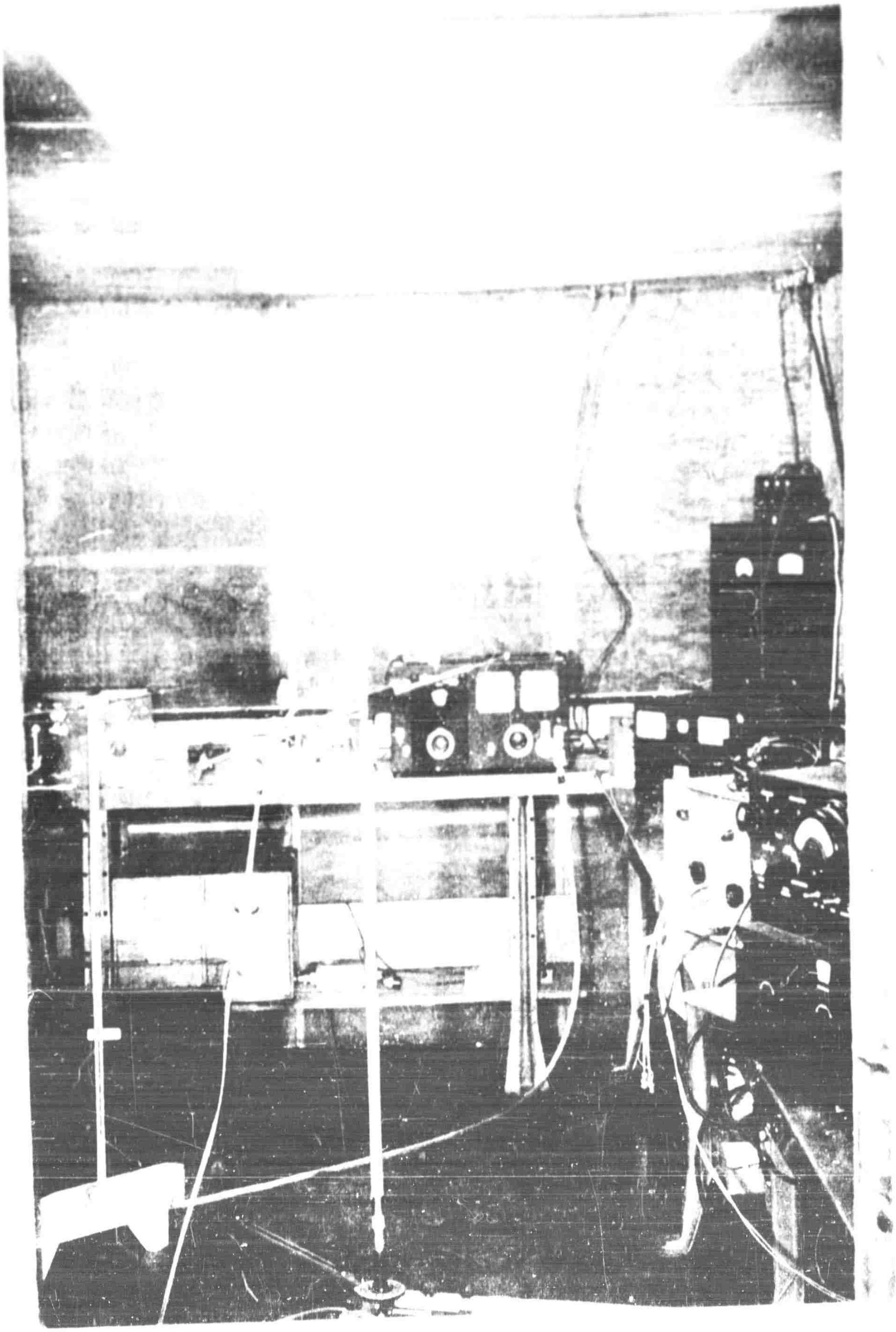


FIGURE 13 - Doorway View of Screen Room Interior

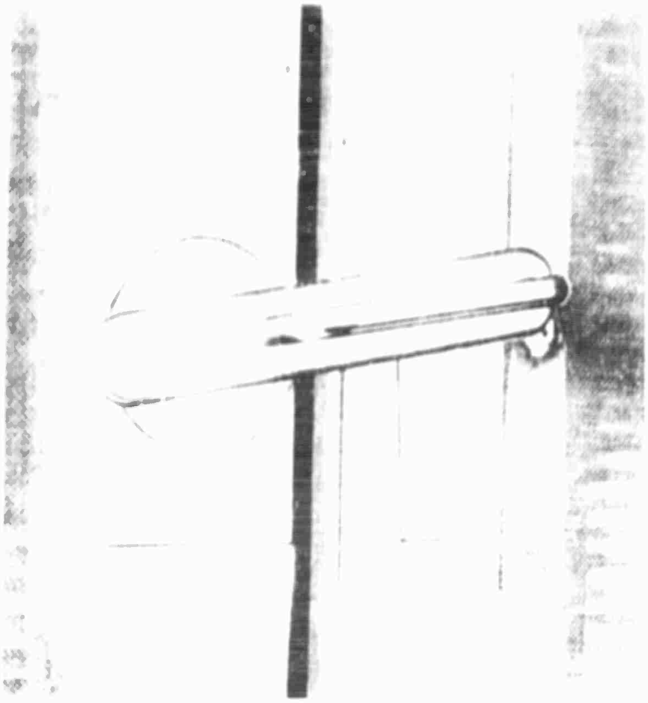


FIGURE 14 - Door Handle and Tightening Wedge Detail
(view from inside room)

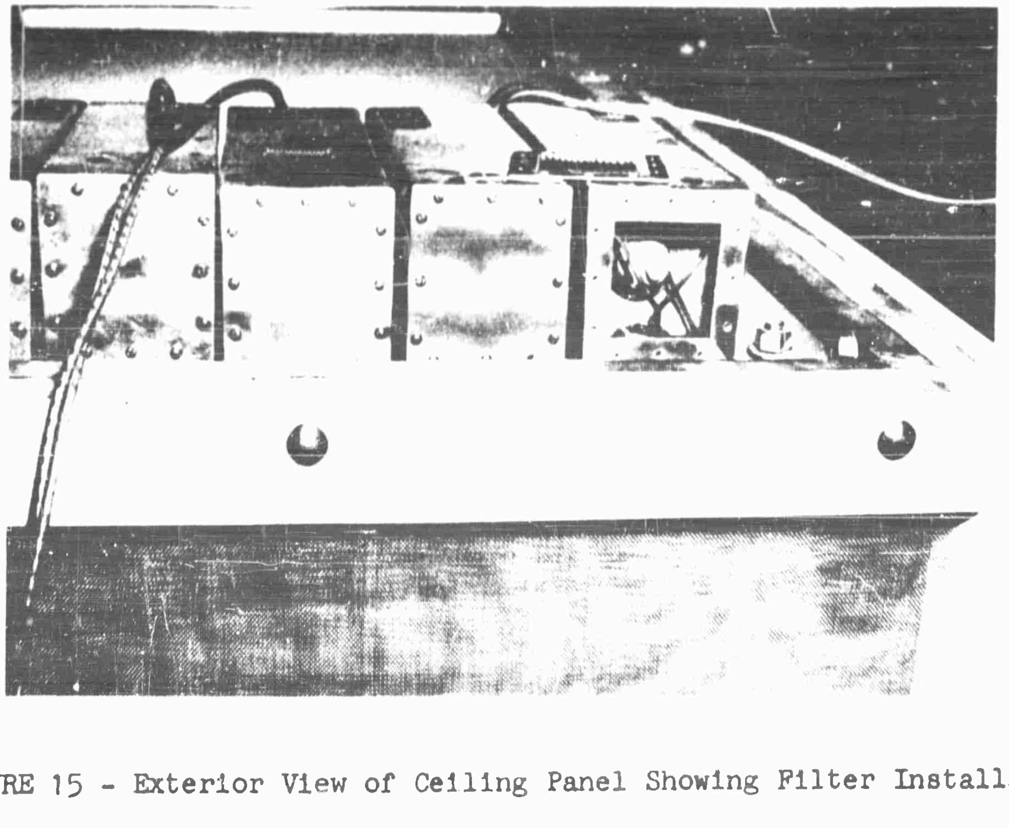


FIGURE 15 - Exterior View of Ceiling Panel Showing Filter Installation

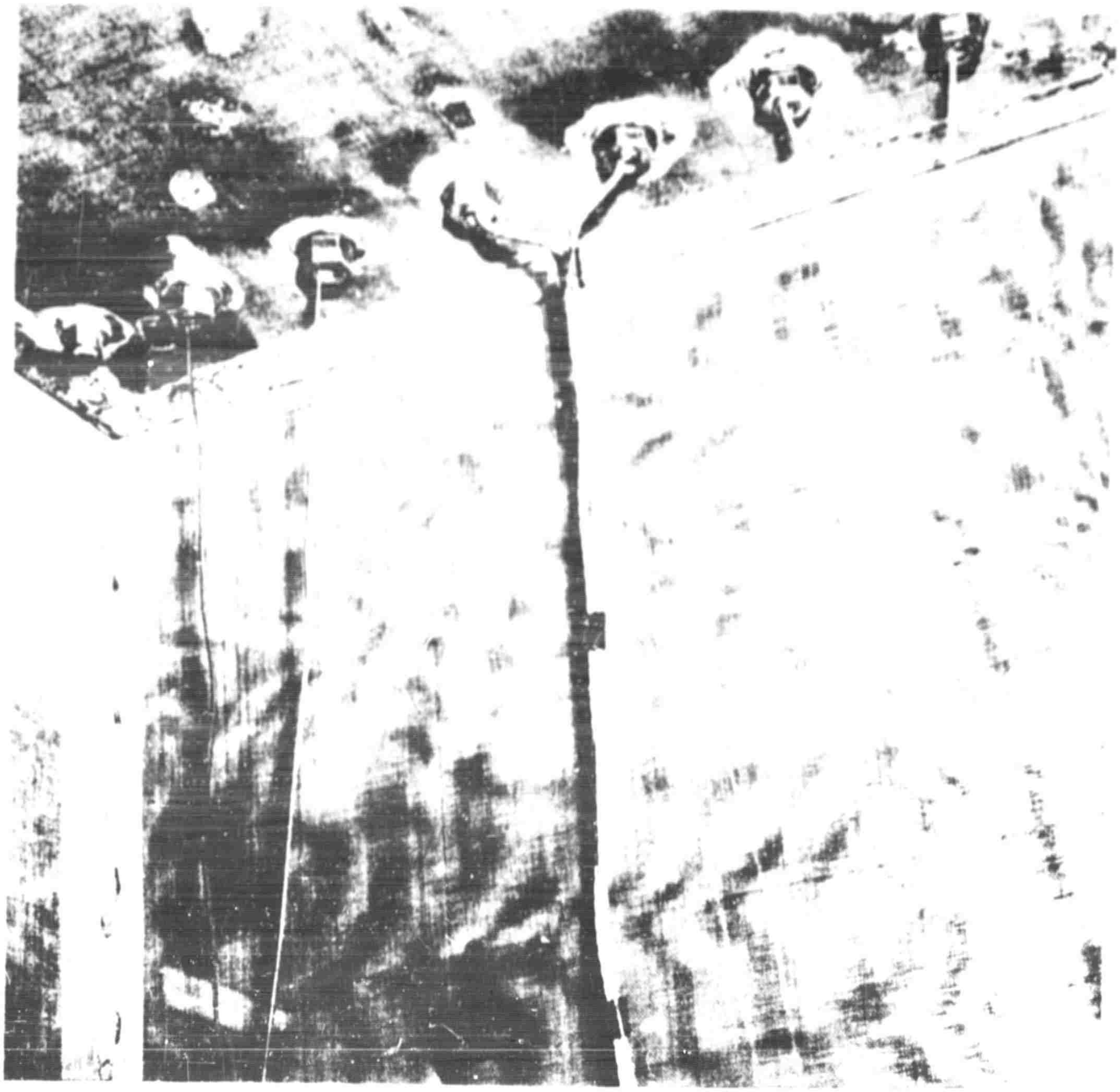


FIGURE 16 - Interior Room View Showing Entry of Filtered Power Lines

Room Improvements, Additions, and Modifications

The following presentation concerns various improvements, additions, and modifications for the standard model of the NADC-AEEL screen room and are either based on actual development experience or are predicated on the known characteristics of the materials involved. No engineering drawings are submitted for these items since in most instances the basic construction of the room remains relatively unchanged. Some of the items listed are covered by a recent NADC service manual for takedown cell-type screen rooms, reference (q). The manual is included as the appendix of this report and is referenced where applicable.

1. Changes in Panel Size - Although the length of the standard model room can be varied readily, changes in room width and height will require changes in the component panel dimensions. Where this is necessary, special size panels can be built using the basic construction of the standard panels. For example, panels 40 inches wide by 8 feet long would make possible a room 10 feet wide by 8 feet high and of any length (in 40-inch multiples) from 80 inches up. A panel width of 40 inches would also allow location of the standard 40-inch wide door panel in any wall of the room.

2. Ceiling Reinforcement - Ceilings of rooms more than 10 feet wide require reinforcement to prevent sagging of the ceiling panels when more than 3 ceiling panels are used. The weight of the panels should be supported by steel I-beams installed on top of the room across the width dimension. On long rooms, the I-beams should be installed at 80-inch intervals.

3. Floor Reinforcement - Where floor loading requirements exceed 120 lb/sq ft, the framework of the floor (screened) panels should be fitted with additional horizontal bracing members. The addition of such members can increase the distributed weight capacity to over 300 lb/sq ft.

4. Silver Plating for Door Fingers - A heavy silver plating applied to the phosphor-bronze door fingers will lower their r-f contact impedance and further reduce the possibility of leakage in the critical area around the screen room door.

5. Double Doors - Where a large entrance to the room is required, an 80-inch door panel can be constructed and equipped with double doors each 40 inches wide.

6. Change in Bolt Size - The 3/8-inch diameter bolts used for bolting together panels of the standard model room can be replaced by 5/16-inch diameter bolts without any loss in panel contact pressures, but with an effective increase in the strength of the panel frames.

7. Change in Pressure Plates - Pressure plates can be improved against possible bending by changing the thickness from 1/8 inch to 1/4 inch. Pressure plates can be improved further by corrugating or dimpling the flat surfaces to prevent rotation of the plates during the bolt tightening operation.

8. Lockwashers - Lockwashers should be used under the nuts in bolting panels together to erect the room. The use of lockwashers minimizes the need for frequent bolt tightening since the takeup afforded somewhat compensates for the tendency of the pressure plates to indent the wood of the panel frames, especially in the case of newly erected rooms.

9. Inside Bolting of Panels - It is sometimes necessary to erect a screen room in such close proximity to the walls or partitions (or the ceiling) of a plant or laboratory as to make outside bolting of some of the screen room panels impossible. This condition can be met by attaching additional frame members to the flush-screened sides of the inaccessible panels to permit bolting from inside the room. The additional frame members should be of similar construction to the frame members provided for inside bolting of floor panels in the standard model room. (See section view "B-B" and floor assembly section of figure 10.)

10. Power Line Filters (See appendix, page 11.) - In addition to the power line filters prescribed for the standard model room, and those mentioned for special microwave applications, low-frequency filters are available which can provide 100 db attenuation from 14 to 500 kc. Filters of this type can be procured from several filter companies and can be series connected with the existing filters. As in the case of the other types, these filters can be operated at power line voltages up to 500 V and at power frequencies up to 800 cps at room temperatures.

11. Transmission Line Connectors (See appendix, page 11.)

12. Metallic Waveguide-Type Attenuators (See appendix, pages 7, 10, 11, and 12.) - Metallic waveguide-type attenuators can be installed in any of the screen room panels to serve as entrance ports for nonmetallic service lines (gas, water, and air hoses) feeding the room. They also can be used as room entrances for rotating-shaft motive power from an external prime mover, providing the shafting entering the room can be made of an insulating material. Waveguide-type attenuators can provide 100 db attenuation over a wide range of frequencies below their designed-for high-frequency cutoff; therefore, their use in many applications will produce little or no impairment of screen room shielding effectiveness.

The waveguides can be fabricated readily from stock tubing, standard extrusions, and from sheet metal. However, it should be noted that the wall thickness of the completed waveguides must at least equal the gauge of the metal used for the shields of the room (a 1/16-inch wall thickness is recommended for waveguides for the NADC-AEEL screen room). To obtain a minimum of 100 db attenuation below cutoff, the length of a circular cross section waveguide should be at least three times its diameter and the length of a rectangular cross section waveguide should be at least four times that of the larger side of the cross section. Cross section dimensions for the two types are further determined by the following:

$$d \leqslant \frac{\lambda}{3.4} \quad \text{and} \leqslant a \quad \frac{\lambda}{4}$$

where

d = diameter of circular cross section waveguide in meters

a = larger side of rectangular cross section waveguide in meters

λ = wavelength in meters of the highest frequency below which a minimum of 100 db attenuation is required.

It can be seen from the above formulas that a waveguide designed to provide 100 db attenuation at the upper microwave frequencies would necessarily have a very small cross section; this obviously limits the utility of waveguides as entrance ports for some screen room

services at these frequencies. However, the problem can be solved for some applications by the use of multiple waveguides. For example, multiple waveguides can be used in supplying forced-air ventilation to screen rooms located in areas where supplementary ventilation is required. In instances of this type the multiple waveguides can take the form of a series of holes in a 1-foot square copper or brass plate attached to the outside of one of the screen room panels at the point where the ventilation duct connects to the room. The thickness of the plate and the diameter of the holes is determined by the required waveguide length and cross section. (For some microwave frequencies, a portion of some types of automobile radiators can be used in lieu of the perforated plate.) The perforated plate replaces both outside and inside screens in the immediate area of the panel in which it is installed, but must be bonded thoroughly to the outside and inside screens of the remainder of the panel. The metal ventilation duct serving the room should not be attached directly to the plate, but should be connected to it by a short duct section of rubber or canvas material. This prevents any interference picked up by the ventilation system duct work from being conducted directly to the screen room panels and also prevents mechanical vibration transfer from the system to the room.

13. Service Entrances (See "Metallic Waveguide-Type Attenuators," above, and in appendix, page 12.)

14. External Drive-Shaft Power - Rotating devices or machines in the screen room can be drive-shaft powered from an external prime mover if special arrangements are provided to prevent r-f interference from leaking into the room at the point where the shafting penetrates the panel screens.

In addition to methods described for this purpose under "Metallic Waveguide-Type Attenuators," above, and those discussed in the appendix under "Service Entrances," the following method is suggested for cases involving large-diameter metallic shafting and high-torque drives. In this method the frame of the prime mover is bonded to the room in such a way that it effectively becomes an extension of the room itself. For example, the frame of a motor can be made integral with the screen room by means of a sheet copper housing or duct enclosing the shaft and connecting the motor end bell to the panel through which the shaft enters the room. Copper plates should be substituted for the panel screens in the area affected and should be bonded (by soldering) to the screens of the remainder of the panel and to the copper duct. The motor end of the duct should be bonded to the motor end bell or frame by clean metal-to-metal contact under pressure. Holes for capscrews can be drilled and tapped for this purpose and in many instances existing bolts or nuts of the end bell or motor frame can be utilized. Ventilation holes in the area of the end bell enclosed by the duct should be screened.

15. R-F Reflectors and Absorbers for Screen Rooms (See appendix, page 18.) - R-F reflectors and absorbers may prove useful in supplementing the screen room shields under certain conditions. For example, there may be rare instances at microwave frequencies when an extremely high-intensity field from an unavoidable, close-proximity source will penetrate the room. In cases of this sort, the interference can be reduced by reflectors and absorbers installed on the outside of the room. Absorbing materials also can be used on the inside of the screen room to provide a closer simulation of free-space conditions by reducing reflections of signals generated by receivers and small transmitters on test in the room. Reflectors can be made from metal sheets, absorbers are available commercially in the form of sheets and blocks and also as a rubberized cloth material.

16. Use of Other Shielding Materials - Shielding materials other than the specified 22-mesh, 15-mil, copper screening can be used with NADC-AEEL type enclosures for improved shielding effectiveness, structural rigidity, and corrosion resistance. Eleven such shielding-material modifications are presented below. Seven of the modifications utilize double-shield cell-type construction; four employ single-shield construction. The panelled arrangement of the basic room design is retained throughout, but one modification dispenses with the panel wood framework because of the inherent stiffness of the shielding material used. It should be noted that the increase in shielding effectiveness afforded by these various shielding materials will depend entirely on the r-f impedance of the bonds at joints between panels of the assembled room. It is of the greatest importance that these impedances be kept as low as possible.

Modification A

Construction:	Double-shield, cell-type
Material:	Hot-tin dipped, 22-mesh, 15-mil copper screening; tin dipped after weaving; coating not to materially reduce open area. (Tests indicate tin dipping increases shielding effectiveness.)
Improved Characteristics:	A slight increase in shielding effectiveness. Improved screen life, rigidity and corrosion resistance.

Modification B

Construction:	Double-shield, cell-type
Material:	Hot-tin or hot-zinc dipped, 22-mesh, 15-mil, iron screening (hardware cloth); tin- or zinc-dipped after weaving. (Screening coarser than 22-mesh is not suitable.)
Improved Characteristics:	A slight increase in shielding effectiveness at the low-frequency end of range and a slight decrease at the high-frequency end. Improved screen life, rigidity, and corrosion resistance.

Modification C

Construction:	Double-shield, cell-type
Material:	Twenty-two mesh, 15-mil, copper-clad screening (11-mil ironcore wire with 2-mil copper covering). Note: No definite information is available as to whether this type of screening can be manufactured.

Improved Characteristics: A slight increase in shielding effectiveness at the low-frequency end of the range and a slight decrease at the high-frequency end.

Modification D

Construction: Double-shield, cell-type

Material: Ten-mil copper sheet. Panel shields should be overlapped on frame periphery using method prescribed for screened panels of standard room. However, corners should not be overlapped but should be butt-joined and soldered. One-inch wide gasket strips of 4-fold, hot-tin dipped screening (16- to 22-mesh, 15-mil, copper) should be inserted in all joints between panels, before panels are bolted together to assemble room. A substitute gasket material (the AEEL-RF Gasket described in reference (r)) may be made up of beryllium-copper or phosphor-bronze strips perforated with small holes to give jagged points on both sides of the strip. Gaskets should have punched holes to accommodate panel bolts. Forced-air ventilation of air conditioning is necessary for this type of room.

Improved Characteristics: Estimated shielding effectiveness of over 100 db from 500 kc to 30,000 mc. Improved shield life, rigidity, and corrosion resistance.

Modification E

Construction: Double-shield, cell-type

Material: Ten-mil galvanized-iron sheet. Panel fabrication details similar to Modification D. Gasket strips and ventilation system required.

Improved Characteristics: Estimated shielding effectiveness of over 100 db from 12 kc to 30,000 mc. Improved shield life, rigidity, and corrosion resistance.

Modification F

Construction: Double-shield, cell-type

Material:	One shield of 10-mil copper sheet and one of 10-mil galvanized iron sheet. Panel fabrication details similar to Modification D. Gasket strips and ventilation system required.
Improved Characteristics:	Estimated shielding effectiveness of over 100 db from 50 kc to 30,000 mc. Improved shield life, rigidity, and corrosion resistance.

Modification G

Construction:	Double-shield, cell-type
Material:	Fifteen-mil copper sheet perforated to give same effect as 22-mesh, 15-mil, copper screening. (Perforating services are commercially available, e.g., from the Harrington and King Perforating Co., and the Diamond Manufacturing Co.) Panel fabrication details similar to Modification D. Gasket strips required.
Improved Characteristics:	A slight increase in shielding effectiveness. Improved shield life, rigidity, and corrosion resistance.

Modification H

Construction:	Single-shield
Material:	Twenty-mil copper sheet. Single shield should be folded over edges of frame periphery; corners should be butt-joined and soldered. Gasket strips and ventilation system required as in Modification D. Note: For single-shield construction the shield-spacing components of the standard panel framework are eliminated and the shielding material is attached directly to the bolting frame. Shielding material on edges of the frame periphery must have punched holes to accommodate panel mounting bolts.
Improved Characteristics:	Estimated shielding effectiveness of over 100 db from 500 kc to 30,000 mc. Simplified construction over double-shield type. Improved shield life, rigidity, and corrosion resistance.

Modification I

Construction: Single-shield

Material: Twenty-mil galvanized iron sheet. Single shield should be folded over edges of frame periphery; corners should be butt-joined and soldered. Gasket strips and ventilation system required as in Modification D.

Improved Characteristics: Estimated shielding effectiveness of over 100 db from 12 kc to 30,000 mc. Simplified construction over double-shield type. Improved shield life, rigidity, and resistance to corrosion.

Modification J

Construction: Single-shield

Material: Twenty-mil copper-clad sheet (12-mil iron covered on both sides with 4-mil copper). Single shield should be folded over edges of frame periphery; corners should be butt-joined and soldered. Gasket strips and ventilation system required as in Modification D.
Note: No definite information is available as to whether the copper-clad sheet material can be manufactured in the sizes required for panel fabrication.

Improved Characteristics: Estimated shielding effectiveness of over 100 db from 50 kc to 30,000 mc. Simplified construction over double-shield type. Improved shield life, rigidity, and corrosion resistance.

Modification K

Construction: Single-shield

Material: Any one of the following metals:
1. 300-mil iron ($\mu = 1{,}000$; $G = 0.17$)
2. 81-mil Mu-metal ($\mu = 80{,}000$; $G = 0.029$)
3. 79-mil Permalloy ($\mu = 80{,}000$; $G = 0.30$)
4. 56-mil Hipernik ($\mu = 80{,}000$; $G = 0.060$)

Single shield should have folded edges and soldered or welded corners. Metal stiffness is such that panel wood framework is not needed. Panels are fastened together by bolts passing through holes punched in the turned-over metal edges. Gasket

strips and ventilation system required as in Modification D. However, panel rigidity may introduce contact discontinuities at the panel joints and panels may have to be soldered or welded together, thus removing the "takedown" construction feature of the room.
Note: The cost of the above metals may be prohibitive for some applications, and other methods may have to be resorted to for the elimination of the interference.

Improved Characteristics: Estimated shielding effectiveness of over 100 db from 60 cps to 30,000 mc. Simplified construction over double-shield type. Improved shield life, rigidity, and corrosion resistance.

SECTION III

SHIELDING EFFECTIVENESS TESTS AND RESULTS

TESTS

Shielding effectiveness tests were developed during the project for determining the performance characteristics of the NADC-AEEL Takedown Cell-Type Screen Room in the presence of various types of fields. These tests were later incorporated in proposed Specification No. MIL-S-4957(Aer) and are generally applicable for use in the testing of various types of shielded enclosures. The tests were based on the material presented in section I of this report and results obtained in NADC tests of numerous enclosures agreed satisfactorily with the theoretical calculations. Four separate tests were developed. Three apply respectively to magnetic fields, electric fields, and plane waves above 1000 mc. Each of these involves the making of true insertion-loss measurements with the wall of the shielded enclosure in and out of the signal path, the signal-level differential in db constituting the enclosure's shielding effectiveness. A fourth test pertains to plane waves below 1000 mc since it was found that true insertion-loss measurements cannot be made in this region because of the pronounced effect of standing waves in the test area. This particular test measures shielding effectiveness on the basis of a db ratio obtained from maximum signal levels received inside and outside the enclosure.

The following description of the NADC tests is presented in handbook style for the convenience of readers who may wish to perform similar tests.

General

Test setups and suggested equipments for performing the NADC Tests are presented in figures 17, 18, 19, and 20. Test equipment views are shown in figures 21, 22, 23, and 24. Each test setup utilizes a signal source and transmitting antenna, outside the enclosure, and a receiving antenna, an attenuator, and a detector inside the enclosure. Loop antennas are used for magnetic fields, rods for electric fields, dipoles for plane waves below 1000 mc, and horns for plane waves above 1000 mc (microwaves).

Signal sources can be signal generators or power oscillators of cw, mcw, or pulsed-cw output. Output power should be sufficient to produce a signal above the inherent noise background of the detector inside the enclosure. Numerous commercial and military equipments can be used as signal sources. Satisfactory sources also can be constructed in the laboratory. (See figures 25 and 26; also figure 11 of appendix.)

Attenuators preferably should be continuously-variable or step-types. They should read directly in db and should be calibrated for the test frequency employed. The attenuator should be impedance matched to the test setup receiving antenna and detector input, and should be capable of supplying attenuation at least equal to the maximum shielding effectiveness of the enclosure being tested; if necessary, several attenuators may be connected in series.

NOTE: The test setup attenuator is not needed if the signal source includes a calibrated output attenuator, or if the detector contains a calibrated input attenuator.

Detectors can be any one of several military and commercial types of radio receivers and field strength meters. The detector serves as the test setup reference level indicator

and should therefore include some form of signal-level indicating device, or should be used in conjunction with an output meter or an oscilloscope.

Basic Test Procedure (Magnetic Fields, Electric Fields, and Plane Waves)

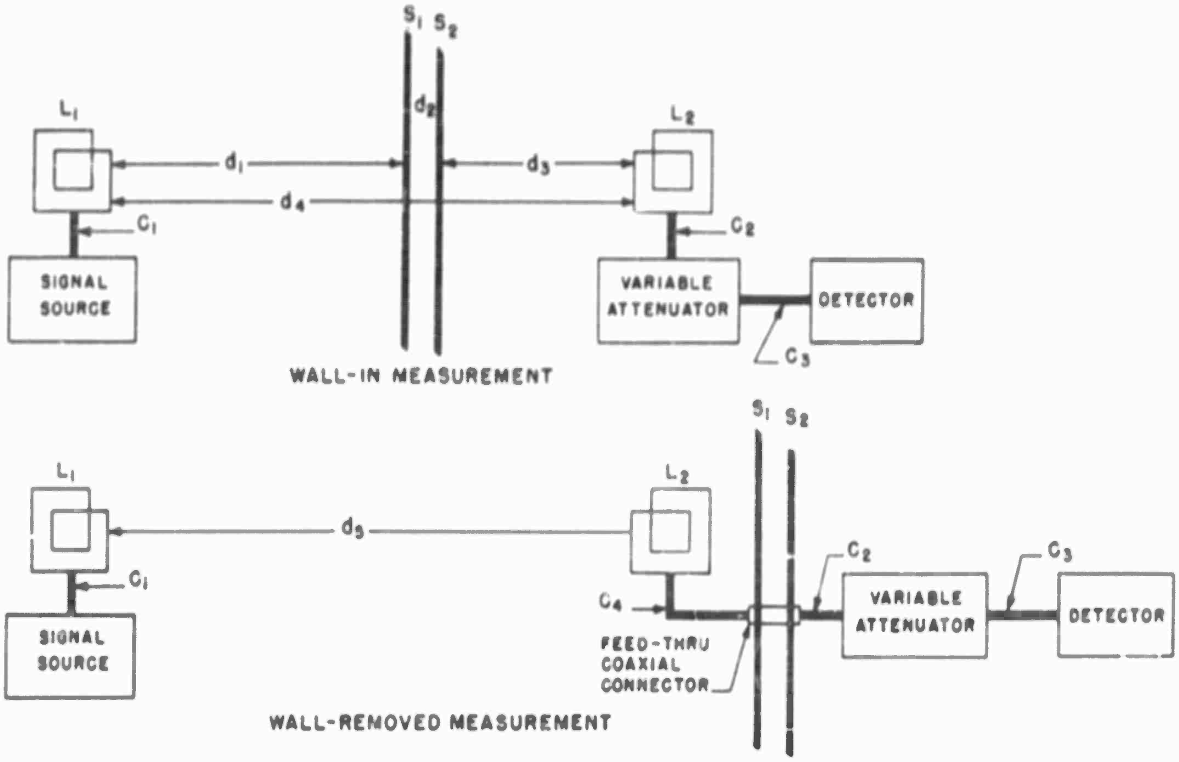
The test setup should be arranged in accordance with the applicable test setup figure (Figures 17, 18, 19, and 20.). The signal source may be located anywhere outside the enclosure at the prescribed distance. There should be no signal-reflecting or -absorbing objects between source and enclosure. Basically, the insertion-loss test procedure consists of placing the equipment in operation and setting the detector gain for maximum sensitivity, inside the enclosure, and then reducing the intensity of the received signal to a level just slightly above the detector's inherent noise background by means of the attenuator. The detector level thus achieved becomes the reference level for the test. The enclosure wall* is next removed and the resulting increase signal at the detector is reduced to the previously established reference level through readjustment of the attenuator. The increase in attenuation required to restore the reference level, in going from the "wall-in" to the "wall-removed" condition, is therefore equal to the shielding effectiveness of the enclosure and is indicated directly in db by the difference in the attenuator settings. The enclosure shielding effectiveness in db is also essentially equal to $20 \log_{10} \frac{E_1}{E_2}$ where E_2 and E_1 are the voltages induced in the receiving antenna with the enclosure wall in and out of the signal path respectively.

Only one wall-removed measurement per test is necessary, but numerous wall-in measurements should be made; the more the better. Under normal test conditions it is virtually impossible to provide a uniform signal field for all portions of an enclosure. For this reason, wall-in measurements should be made for all wall and ceiling areas (and floor areas, if accessible), particularly those areas of possible shielding discontinuity such as the door area and panel joint areas. Exploring the enclosure in this manner necessitates relocating both the transmitting and receiving antennas for each measurement and requires the maintaining of the prescribed antenna distances relative to each other and to the enclosure. (This procedure is deviated from in the special test designed for plane waves below 1000 mc, as explained later.) The attenuator settings will vary somewhat for the various areas tested. The readings should be recorded and the highest reading obtained should be considered the wall-in reading and used for comparison with the wall-removed reading. The difference between these two readings then indicates the minimum shielding effectiveness of the enclosure for the particular test frequency used.

In instances where the test setup signal is not strong enough, or the detector not sensitive enough, the test reference level will of necessity be the detector's inherent noise background and variations in shielding effectiveness for various areas of the enclosure may be impossible to determine. Attenuating the signal to this noise background level during the wall-removed measurement will merely indicate that the enclosure provides at least an equivalent amount of shielding effectiveness; how much more it provides cannot be determined without an improved signal source or detector.

Although in some instances the enclosure wall can be removed literally by opening the enclosure door, or physically removing one or more of the enclosure panels, an equally effective and more practical wall-removed method involves taking the receiving antenna

* The term "wall" is used to apply to the entire shielded enclosure or to that portion of the enclosure lying directly in the signal path, i.e., wall, ceiling, or (if accessible) floor.



d_1 = 12 inches

d_2 = 1 inch (shield separation)

d_3 = 12 inches

d_4 = 25 inches ($d_1 + d_2 + d_3$)

d_5 = d_4

S_1 = Outer shield

S_2 = Inner shield

L_1 = Transmitting antenna; low impedance circular loop of 1 turn No. 6 AWG copper wire. Loop diameter = 12 inches for 200 kc. Loop may be oriented at any angle in a plane perpendicular to enclosure wall.

L_2 = Receiving antenna; circular loop, same diameter as L_1, but with 1 to 2 turns. Loop positioned in same plane as L_1.

Signal Source = Low-impedance source of adequate output at test frequency such as: T-47/ART-13 Transmitter, General Radio Model 805A Signal Generator, Rollin Model 20 Signal Generator, and high peak power source shown in figure 11 of appendix of this report. (Peak power source is adaptable to other frequencies by change of LC components.)

Attenuator = Variable type with low-impedance input (e.g., 50-ohm Western Electric No. KS-9534L2); calibrated in db at the test frequency. Attenuator not required if signal source includes calibrated output attenuator, or if detector includes calibrated input attenuator.

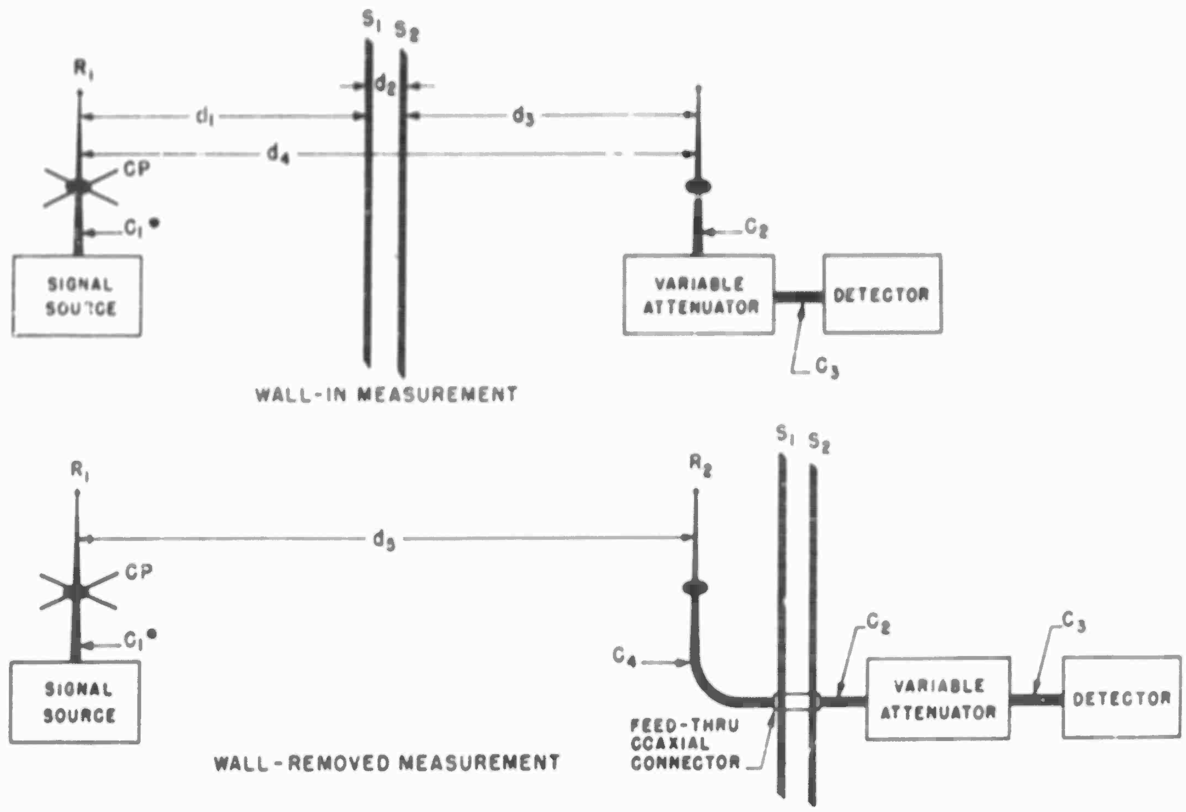
Detector = Detector of adequate sensitivity (e.g., DZ-2 Radio Receiver, or AN/PRM-1 Field Strength Meter) tuned to test frequency. Detector is used as reference level indicator and should provide signal level indication or should be used with output meter or oscilloscope.

C_1, C_2, C_3, and C_4 = Shielded transmission-line cables. Should be short as possible and may be eliminated where test setup components can be direct coupled.

Coaxial Connector = Transmission-line connector installed in enclosure wall and bonded to S_1 and S_2.

Test Frequency = Any frequency in 18 kc to 18 mc range. A spot frequency in the 150 to 200 kc range may be used.

FIGURE 17 - Shielding Effectiveness Test Setup for Magnetic Fields (Wave Impedance $\ll$ 377 Ohms)



d_1 = 12 inches

d_2 = 1 inch (shield separation)

d_3 = 12 inches

d_4 = 25 inches ($d_1 + d_2 + d_3$)

d_5 = d_4

S_1 = Outer shield

S_2 = Inner shield

R_1 = Transmitting antenna; high impedance rod type, 41 inches long for frequencies up to 18 mc. Rod may be oriented in any position parallel to wall of enclosure.

CP = Counterpoise for transmitting antenna.

R_2 = Receiving rod antenna; similar to R_1, but without counterpoise.

Signal Source = High-impedance source of adequate output at test frequency such as: T-47/ART-13 Transmitter, General Radio Model 805A Signal Generator, Rollin Model 20 Signal Generator, and high peak power sources shown in figure 25.

Attenuator = Capacity-type, variable attenuator with high-impedance input (e.g., Ferris Model 32-XA3, or 32-XA4) calibrated in db at the test frequency. (Attenuator not required if signal source includes calibrated output attenuator, or if detector includes calibrated input attenuator.)

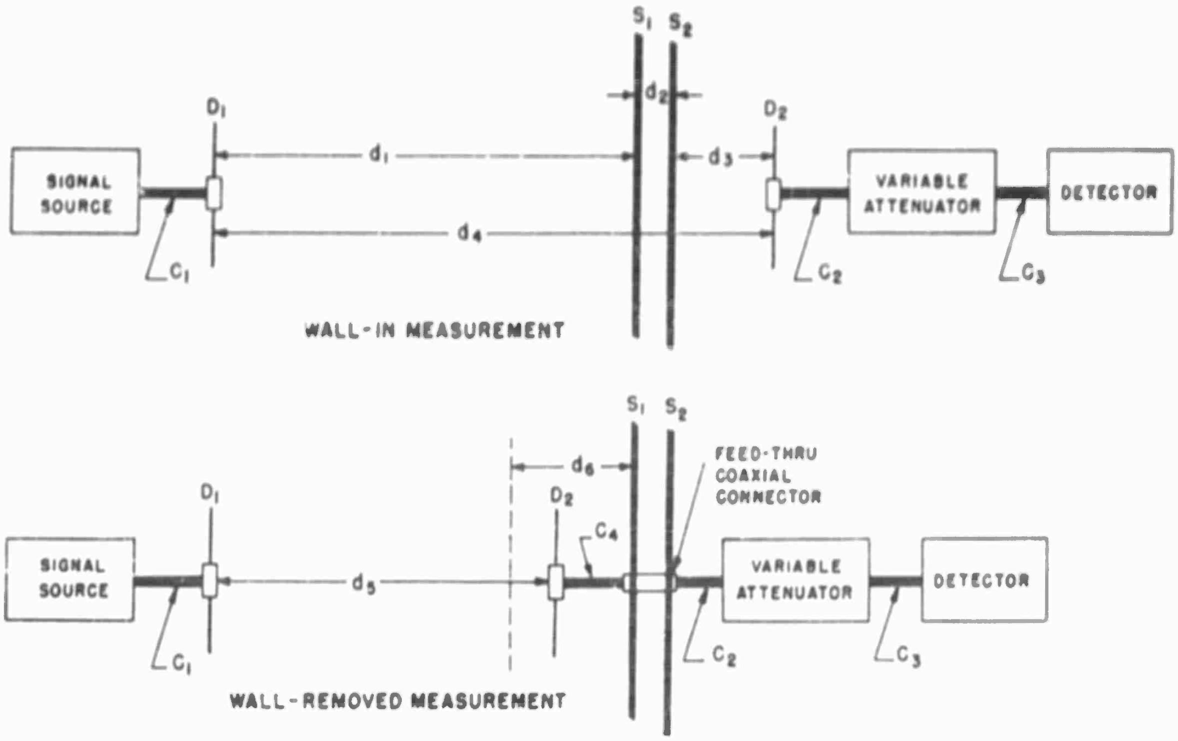
Detector = Detector of adequate sensitivity (e.g., BC-348Q Radio Receiver, Ferris Model 32A Field Strength Meter, or AN/PRM-1 Field Strength Meter) tuned to test frequency. Detector is used as reference level indicator and should provide signal level indication or should be used with output meter or oscilloscope.

C_1, C_2, C_3, and C_4 = Shielded transmission-line cables. Should be short as possible and may be eliminated where test setup components can be direct coupled.
*If very high impedance signal source is used, shielded cable C_1 should be replaced by open-wire line to prevent capacitive loading. Counterpoise of R_1 may have to be eliminated for same reason.

Coaxial Connector = Transmission-line connector installed in enclosure wall and bonded to S_1 and S_2.

Test Frequency = Any frequency in 18 kc to 18 mc range. Suggested spot frequencies: 200 kc, 1.0 mc, and 18.0 mc.

FIGURE 18 - Shielding Effectiveness Test Setup for Electric Fields (Wave Impedance $\gg$ 377 Ohms)



d_1 = Distance as great as possible (more than 2λ); limited only by power of a signal source.

d_2 = 1 inch (shield separation)

$d_3 \geqslant$ 2 inches

d_4 = $d_1 + d_2 + d_3$

$d_5 \leqslant d_1$ - 2 inches; and $\geqslant d_1 - \lambda/4$

$d_6 \geqslant$ 2 inches; and $\leqslant \lambda/4$. Receiving dipole is moved within this area for point of maximum signal pickup (highest attenuator setting).

S_1 = Outer shield

S_2 = Inner shield

D_1 = Transmitting antenna; tuned dipole = $\lambda/2$ at test frequency. If tuned dipole is used with single coaxial line, dipole should be balanced type similar to AT-275/URM-28 of Specification No. MIL-I-6181. (Other suitable antennas are: AT-141/ARC, used with AN/ARC-27 equipment; AT-49/APR-4, used with AN/APR-4 equipment; and AT-90/AP, used with AN/APT-5 equipment.) Antenna should be oriented to produce maximum field intensity at enclosure.

D_2 = Receiving antenna, same as D_1.

Signal Source = Source of adequate output at test frequency such as: AN/ARC-27 Transmitter, Rollin Model 30A Signal Generator, AN/APX-6 Transpondor, AN/APT-5 Radar Transmitter, or high peak power 400-mc source shown in figure 26.

Attenuator = Variable type with low-impedance input (e.g., 50-ohm Western Electric No. KS-953462) calibrated in db at test frequency. (Attenuator not required if signal source includes calibrated output attenuator, or if detector includes calibrated input attenuator.

Detector = Detector of adequate sensitivity (e.g., radio receivers AN/APR-4, AN/URM-28 and AN/ARC-27; or field strength meters such as Measurements No. 58, TS-587/U, or AN/URM-17) tuned to test frequency. Detector is used as reference level indicator and should provide signal level indication or should be used with output meter or oscilloscope.

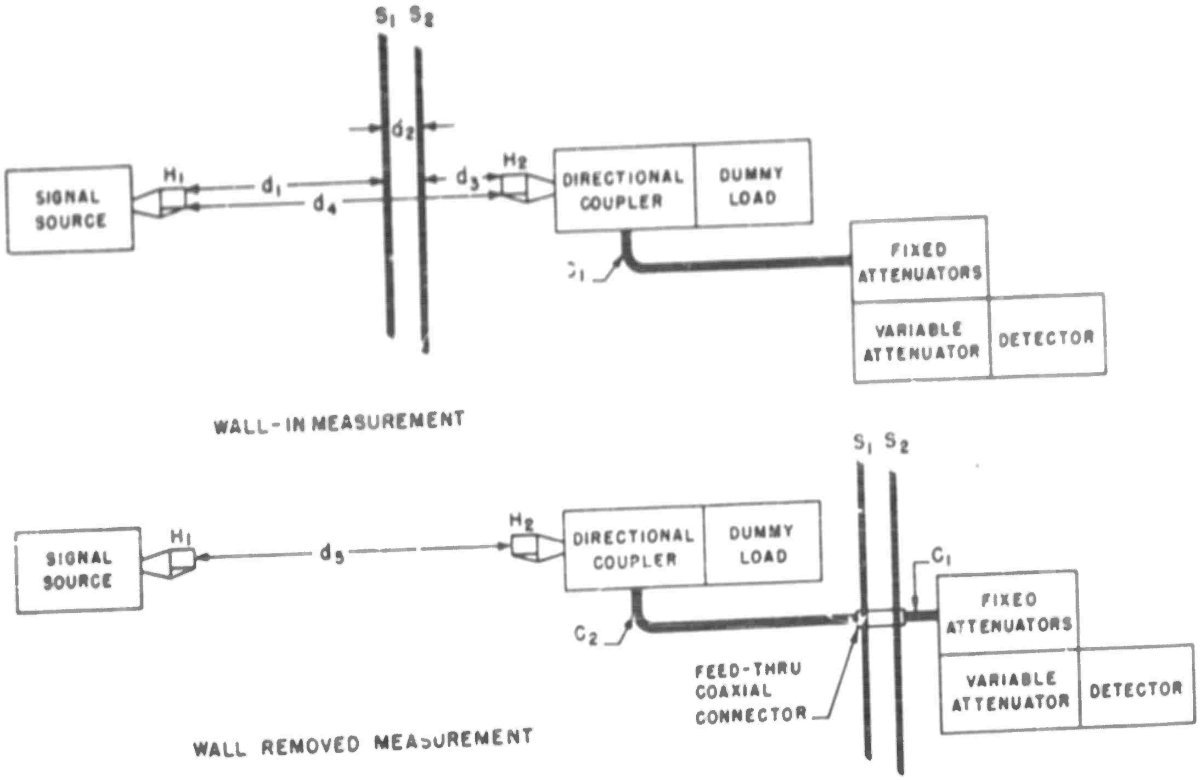
C_1, C_2, C_3, and C_4 = Shielded transmission-line cables. Should be short as possible and may be eliminated where test setup components can be direct coupled.

Coaxial Connector = Transmission-line connector installed in enclosure wall and bonded to S_1 and S_2.

λ = Wavelength in meters at test frequency.

Test Frequency = Any frequency in 18 to 1000 mc range. A spot frequency of 400 mc may be used.

FIGURE 19 - Shielding Effectiveness Test Setup for Plane Waves Below 1000 mc (Wave Impedance = 377 Ohms)



$d_1 >$ 12 inches

$d_2 =$ 1 inch (shield separation)

$d_3 =$ 12 inches

$d_4 =$ 25 inches ($d_1 + d_2 + d_3$)

$d_5 = d_4$

$S_1 =$ Outer shield

$S_2 =$ Inner shield

$H_1 =$ Transmitting antenna (horn), e.g., AT-245/APG-30, or AT-39/AP.

$H_2 =$ Receiving antenna (horn), e.g., AT-273/UPM.

Signal Source = Source of adequate output at test frequency such as: AN/APS-4, AN/APS-42, and APG-30 radars, and Sperry Klystron Signal Source Model 444.

Directional Coupler = Coupler calibrated in db at the test frequency.

Dummy Load = TS-108/AP or equivalent type.

Fixed Attenuators = Waveguide-type attenuators calibrated in db at test frequency. (Actual number used to be determined by the attenuation afforded per unit and by the expected shielding effectiveness of the enclosure under test.)

Variable Attenuator = Variable, waveguide type; calibrated in db at test frequency.

Detector = Detector of adequate sensitivity tuned to test frequency such as TS-148/UP Spectrum Analyzer, or a sufficiently sensitive crystal detector. Detector is used as reference level indicator and should provide signal level indication or should be used with an output meter or oscilloscope.

$C_1 =$ RG-9/U transmission line cable; as short as possible.

$C_2 =$ RG-9/U transmission line cable; must be of identical length for wall-in and wall-removed measurements.

Coaxial Connector = Transmission-line connector installed in enclosure wall and bonded to S_1 and S_2.

Test Frequency = Any frequency in the 1000 to 10,000 mc range. A spot frequency in the "X" band (9375 mc) may be used.

FIGURE 20 - Shielding Effectiveness Test Setup for Plane Waves Above 1000 mc (Wave Impedance = 377 Ohms)

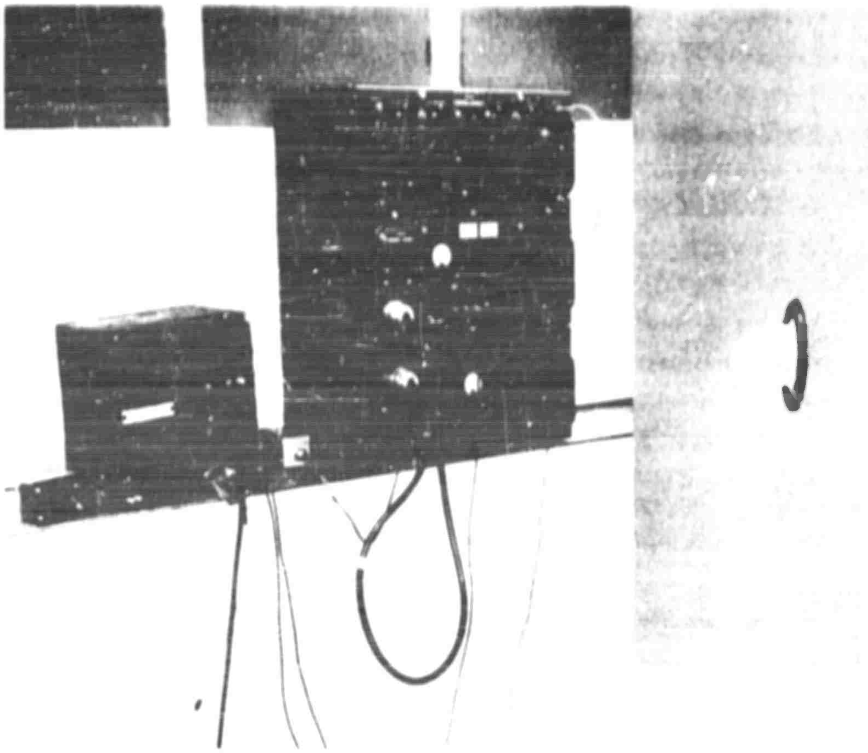


FIGURE 21 - AN/APX-6 Transponder Used as Signal Source in Shielding Effectiveness Test at 1000 mc

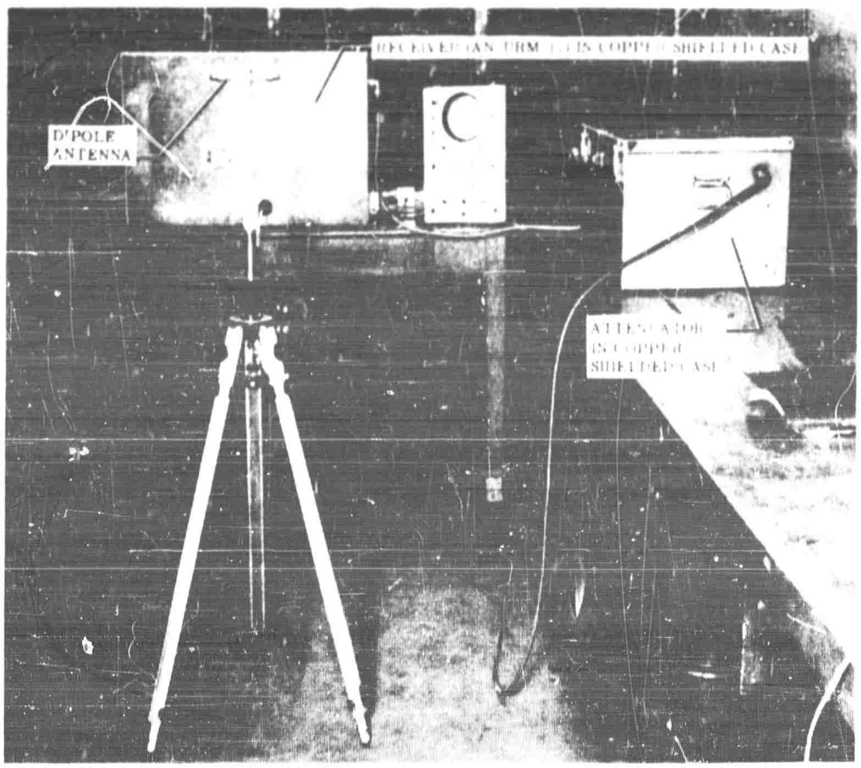


FIGURE 22 - Setup for Wall-In Measurements at 1000 mc

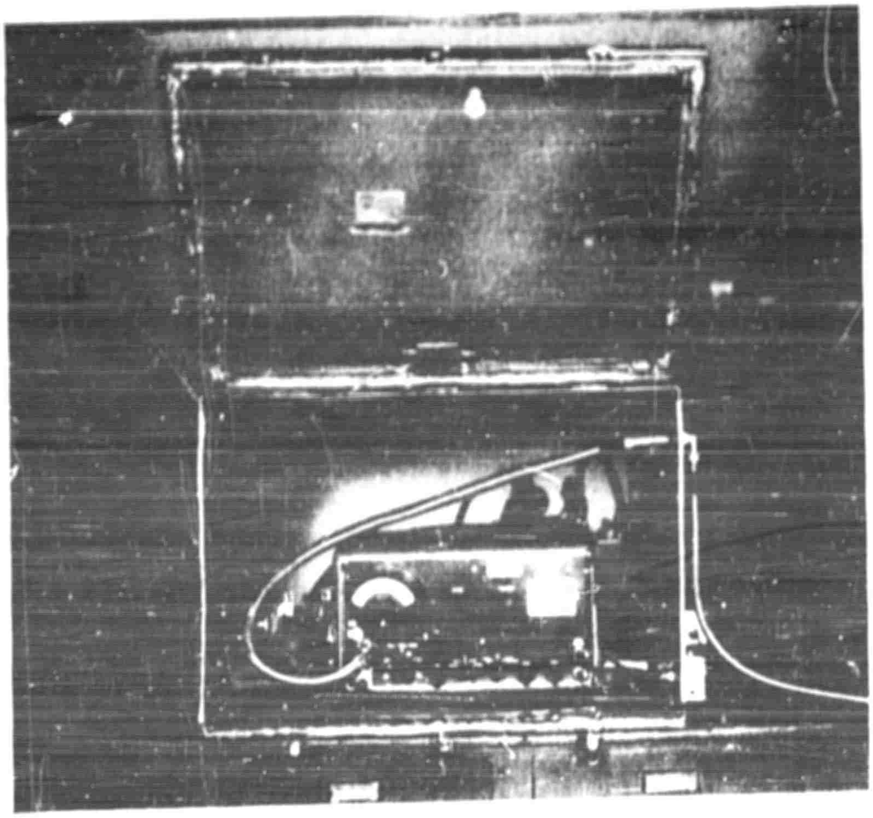


FIGURE 23 - AN/URM-17 in Copper Shiel Case

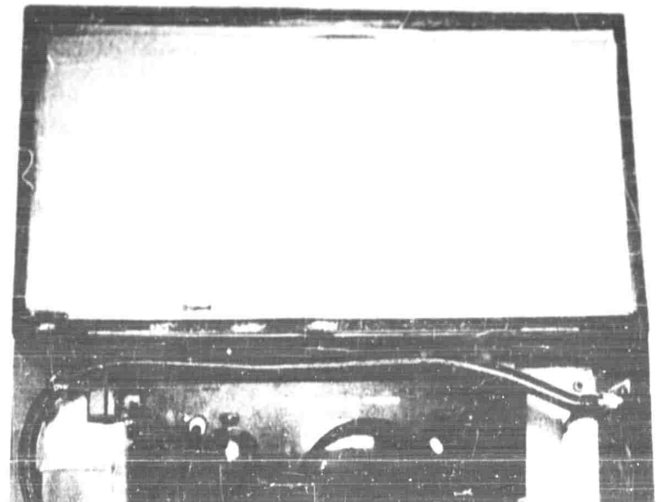


FIGURE 24 - Western Electric No. KS-9534L2 Attenuators in Copper Shielded Case

outside the enclosure and adjusting its position (and that of the transmitting antenna) so as to duplicate the antenna separation and orientation of the wall-in measurements. (See figures 17, 18, and 20.) In placing the receiving antenna outside the enclosure, it is essential that it be located far enough in front of the enclosure wall to prevent the antenna impedance from being affected by the wall proximity. This has been allowed for in the prescribed test setup distances, but there may be some test environments which will call for slight additional shifting of the receiving antenna. In such instances, the transmitting antenna must be shifted by a like amount to restore the antenna separation distance of the wall-in measurements.

Because of the strong signal field existing outside the enclosure, the attenuator and detector should be left inside and connected to the receiving antenna by means of a short transmission line cable connected to a transmission line connector installed in one of the enclosure wall panels, as shown in the figure. This addition to the antenna cabling must be of the proper impedance and should be kept as short as possible. Where an appreciable increase in cable length is unavoidable, the cable attenuation should be allowed for when comparing wall-in and wall-removed measurements. In instances where it is necessary to locate the attenuator and detector outside the enclosure, the cases of both units should be tested for r-f leakage (signal pick-up through the case) before making the wall-removed measurement. The test is effected by temporarily disconnecting the receiving antenna and capping and center-conductor grounding the attenuator input (or detector input, if attenuator is integral with detector unit). Under these conditions, there should be no change in the detector inherent noise background when the signal source is turned on and off. If leakage exists, the detector and attenuator should be placed in a copper shielded case.

NOTE: The case-leakage test also should be performed on the attenuator and detector prior to making wall-in measurements.

Plane Waves Below 1000 mc

Figure 19 shows the test setup pertaining to plane waves below 1000 mc. As stated previously, true insertion-loss measurements cannot be made in this region because of the pronounced effect of standing waves in the test area. The test in this instance involves a db ratio obtained from maximum signal levels received outside as well as inside the enclosure. Exploration for the point of maximum signal indication is effected by moving the receiving antenna alone. After the interior of the enclosure has been explored, the receiving antenna is taken outside and the specified area (d_6) in front of the enclosure wall is similarly explored. The transmitting antenna remains at the original distance dictated by the test setup; consequently, in this particular test distance d_4 and d_5 do not remain equal in going from the wall-in measurements to the wall-removed measurement. As in the case of the other tests described in this section, the signal source can be located anywhere outside the enclosure at the prescribed distance from the enclosure wall. However, after the point of maximum signal has been found for the wall-in measurement, a somewhat truer indication of the enclosure's performance could be obtained if the wall-in measurements were repeated with the signal source relocated in line with the point of maximum signal determined in the first set of measurements. This new maximum should then be the one used for comparison with the wall-removed measurement to determine the shielding effectiveness of the enclosure.

Plane Waves Above 1000 mc (Microwaves)

In the test applying to plane waves above 1000 mc (figure 20), the maximum as well as the minimum shielding effectiveness should be determined and both values recorded. This

is recommended procedure for the testing of double-shield type enclosures because of the considerable variation in the reflection-loss component of shielding effectiveness at microwave frequencies. As explained in section I of this report, the variation is caused by the fact that the separation of the shields can amount to odd multiples of $\lambda/4$ and multiples of $\lambda/2$ at certain frequencies within this region and can cause the reflection loss contribution to over-all shielding effectiveness to vary anywhere from +0 db to +70 db (maximum). For the same reason, minute variations in the nominal 1-inch shield separation distance (caused by unavoidable enclosure fabrication discrepancies and, for screened enclosures, normal shield sag and bellying) produce comparable variations in shielding effectiveness. At 10,000 mc, for example, a 0.3-inch variation in the 1-inch shield spacing can represent a variation in shielding effectiveness of 50 db.

Because of these variables, results of shielding effectiveness tests are less definitive and more difficult to repeat at microwave frequencies than at the lower frequencies (see shaded area of figure 8); thus the necessity for testing for both the minimum and the maximum shielding effectiveness. Two methods are suggested: (1) determining minimum and maximum shielding effectiveness by using several test frequencies spaced 3000 to 6000 mc apart, and (2) using a single test frequency and determining minimum and maximum shielding effectiveness by varying the enclosure shield spacing (d_2 of figure 20) during the wall-in measurements. This can be accomplished readily for screen rooms and light-gauge sheet metal enclosures by a slight pushing together and pulling apart of shields S_1 and S_2 at each measurement point. (Obviously this method cannot be used in tests of enclosure whose shield stiffness is such as to prevent sufficient shield movement.) With either method, the lowest minimum and highest maximum recorded should be used for the final determination of the enclosure's minimum and maximum shielding effectiveness.

The suggested test setup components of figure 20 include radar transmitters as signal sources. A radar signal source should be located far enough from the enclosure to prevent the source from being damaged by reflected energy. The actual number of attenuators required for the test setup of figure 20 is dependent upon the attenuation provided by the particular type of units used and by the expected maximum shield effectiveness of the enclosure under test. The directional coupler and dummy load are included in the test setup to prevent signals from a high-intensity source from exceeding the power rating of the attenuators, but can be eliminated during wall-in measurements if desired. They can be eliminated for the wall-removed measurement also if the average radiated power of the signal source does not exceed the rating of the attenuators by more than two or three times and if operation of the source can be limited to not more than 30 seconds and repeated, where necessary, at intervals of not less than 1 minute.

The directivity of the horn-type antennas used in this test permits a possible alternative wall-removed method in which a portion of the enclosure wall is removed literally. This simply involves placing the antennas at wall-in measurement distances on either side of the enclosure door and then opening the door for the wall-removed measurement. The use of horns also simplifies the making of the case-leakage test. In this instance, the signal can be removed effectively from the input of the attenuators and detector by placing a metal plate over the mouth of the receiving horn.

NADC TEST RESULTS

The NADC-AEEL Takedown Cell-Type Screen Room was tested in accordance with the methods described above. The following test equipment was used:

Low Impedance Fields (Magnetic Fields)

DZ-2 Radio Receiver
AN/PRM-1 Field Strength Meter
AN/ART-13 Transmitter, 0.2 to 18 mc, 100 w
General Radio Company Model 805A Signal Gene 'or
Rollin Company Model 20 Signal Generator
Peak-power magnetic field source shown in figure 11 of appendix
Radiating and receiving antennas described in figure 17
50-ohm L and N attenuators (Western Electric Company No. KS-953462 and KS-655098)
Sheet copper enclosures to shield test instruments when necessary
50-ohm cables and connectors
Test Frequencies = 18 kc, 200 kc, and 10 mc

High Impedance Fields (Electric Fields)

BC-348Q Radio Receiver
Ferris Instrument Corporation Model 32A Field Strength Meter
Ferris Instrument Corporation Model 32-XA3 and 32-XA4 Attenuators
AN/PRM-1 Field Strength Meter
AN/ART-13 Transmitter, 0.2 to 18 mc, 100 w
General Radio Company Model 805A Signal Generator
Rollin Company Model 20 Signal Generator
Peak-power electric field sources shown in figure 25
41-in. rod antennas described in figure 18
Sheet copper enclosures to shield test instruments when necessary
Test Frequencies = 18 kc, 200 kc, and 18 mc

Plane Waves

AN/URM-28 Receiver
TS-587/U Field Strength Meter
Measurements Corporation Model 58 Field Strength Meter
AN/URM-17 Field Strength Meter
AN/ARC-1 Transmitter, 116 to 150 mc, 5 w
AN/ARC-12 Transmitter, 225 to 350 mc, 6 w
RT-178/ARC-27 Transmitter, 225 to 400 mc, 20 w
AN/APX-6 Transponder
Peak power 400-mc source shown in figure 26
AT-275/URM Antenna
AT-141A/ARC Antenna
AT-49/APR4 Antenna
AS-133/APX Antenna
50-ohm L and N attenuators (Western Electric Company No. KS-953462 and KS-655098)
Sheet copper enclosures to shield test instruments when necessary
50-ohm cables and connectors
Test Frequencies = 134.68, 233.8, 399.9, and 952 mc

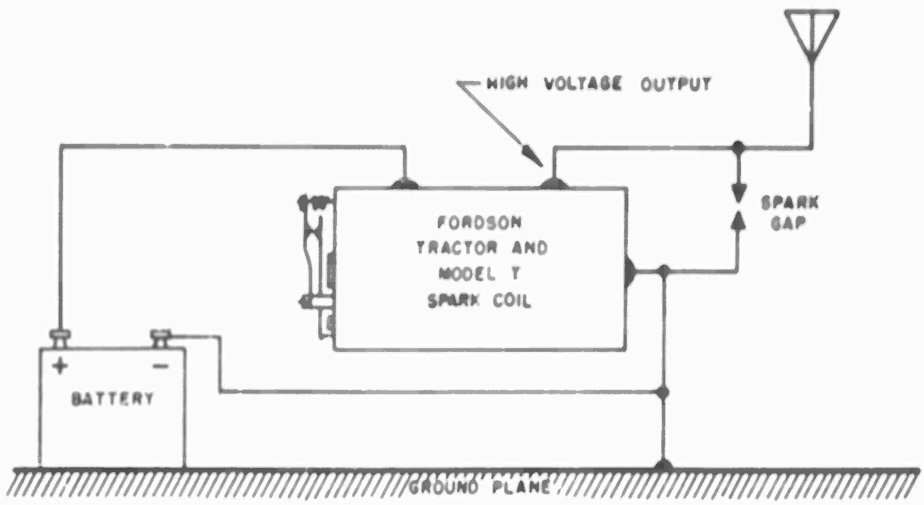
Plane Waves at Microwave Frequencies

TS-148/UP Spectrum Analyzer
AN/APS-4 Radar 9375 ±55 mc, 40 kw pulse power
AN/APS-42 Radar 9389 ±10 mc, 40 kw pulse power
AN/APG-30 Radar 9375 ±40 mc, 5 kw pulse power
AT-39/AP Horn Antenna
AT-245/APG-30 Horn Antenna
AT-273/UPM Horn Antenna
TS-108/AP Dummy Load
CU-217/U Directional Coupler
Polytechnic Research & Development Company constant and variable wave-guide attenuators
Coax-to-waveguide coupler
RG-9/U Cable, 0.4 db loss/foot at 10,000 mc
Test Frequency = 9375 mc, nominal

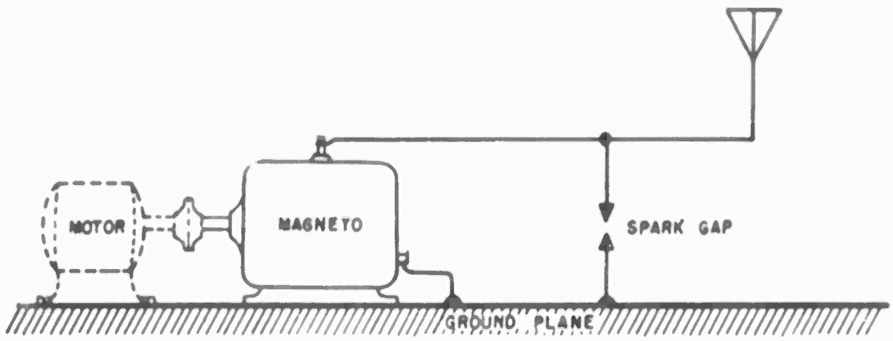
Some 10 rooms were tested during the course of the project. Four of these were at least six years old, had been used continuously, and had been disassembled and assembled for relocation at least eight times during the six-year period. Data obtained in tests of the six-year-old rooms were used for plotting the typical performance curves shown in figure 8. New rooms were also tested and a comparison of data obtained in tests of the new and the old rooms showed negligible differences in shielding effectiveness, not more than 2 to 3 db.

A study of all the test data obtained showed that the NADC-AEEL Takedown Cell-Type Screen Room provided an average shielding effectiveness of 100 db from 0.15 to 10,000 mc. Plots of test curves agreed with the theory in that the shielding effectiveness of a screen room is a variable quantity influenced by numerous factors such as wave impedance, distance from signal source to room, wire diameter of the screening material, percentage of open area afforded by the screen mesh, and the spacing between screens. (These factors were discussed in detail in section I.) Inspection of the typical over-all curve of figure 8 shows a decrease in shielding effectiveness below the 100-db average at both the low- and high-frequency ends. The decrease at the low-frequency end occurs when a magnetic-field source is as close as 12 inches from the room. The decrease at the high-frequency end occurs when the screen spacing becomes a multiple of $\lambda/2$ of the frequency.

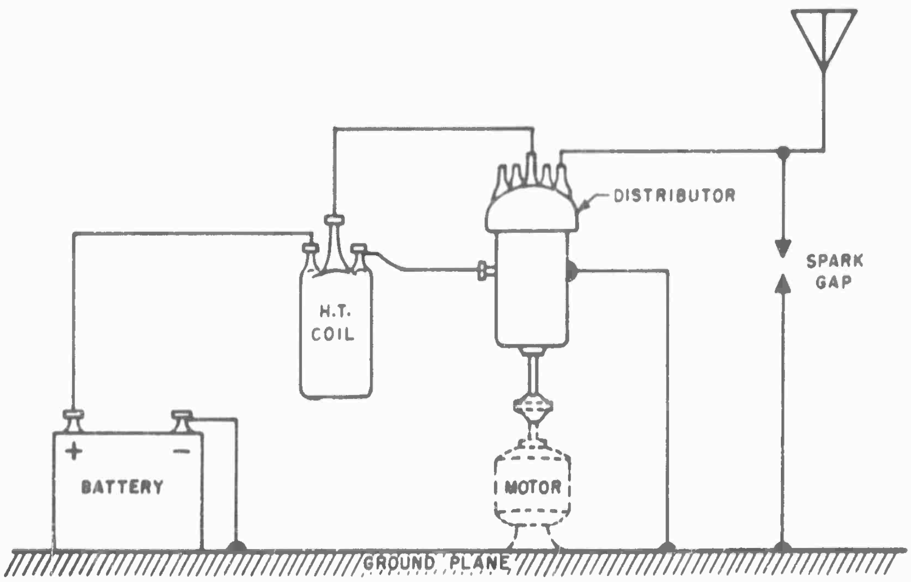
Considerable effort was made to test the NADC-AEEL room under more stringent conditions than those encountered in most plant and laboratory screen room environments; therefore, the minimum (rather than maximum) shielding effectiveness was determined for each type of field. Twelve inches was used as the source-to-room distance for magnetic fields and electric fields. This distance was chosen primarily to provide a severe test for magnetic fields (the most difficult field to shield against) and it was felt that 12 inches was considerably less than existing source-to-room distances for this type of field in the majority of screen room installations. The 12-inch distance was an arbitrary choice but, since it was also used for electric fields, proved to be a reasonable choice. A distance shorter than 12 inches results in lower shielding effectiveness for magnetic fields, but higher shielding effectiveness for electric fields; conversely, a distance greater than 12 inches results in higher shielding effectiveness for magnetic fields, but lower shielding effectiveness for electric fields. The room provides much greater shielding effectiveness for electric fields than for magnetic fields at all distances. This is caused by the fact that the wave impedance for electric fields decreases with the increase in distance but never



SPARK COIL SOURCE

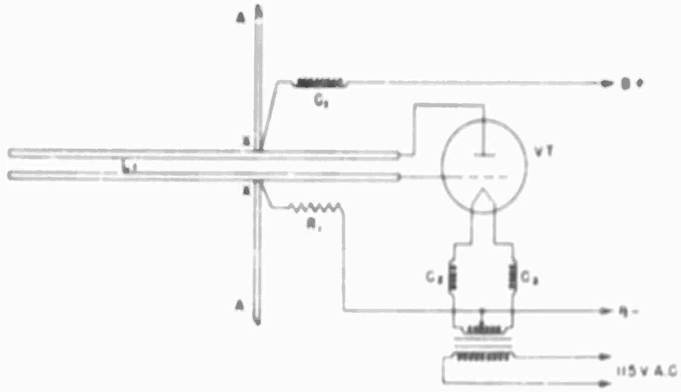


MAGNETO SOURCE



IGNITION SYSTEM SOURCE

FIGURE 25 - Peak Power Sources for Electric Fields



A	=	Half-wave horizontal dipole: Each λ/4 element of No. 12 bus bar 7 in. lg. Elements shall have fuse clip soldered to one end to permit adjustment along L_1
C_1	=	Choke; 40 turns No. 20 wire air-wound on 1/4 in. dia; self-supporting
C_2, C_3	=	Chokes; 30 turns No. 18 wire air-wound on 1/4 in. dia; self-supporting
L_1	=	Tuned-line tank: Two 1/4-in. OD parallel copper rods 11-1/2 in. long and spaced 1/4 in. apart; horizontally mounted on 2-in. porcelain standoff insulators on phenolic board. Ends of rods can be drilled to accept plate and grid pins of vacuum tube
R_1	=	15,000 ohms, 10 w.
T	=	Filament transformer: 2-1/2 V secondary, center-tapped. (Two dry cells with voltage-limiting resistor may be used.)
VT	=	Vacuum tube: W.E. 316A; Ep = 450 V, Ip = 80 ma, Ef = 2.0 V, If = 3.65 amp, Ig = 12 ma, output = 7.5 W.
B+	=	Plate voltage: 450 V dc from dry cells or rectified a-c power supply; or 1000 V ac, rms, 60 cycles, from high-voltage transformer
XX	=	Approximate location (4-1/2 in. from tube end of L_1) of dipole elements and connection points for C_1 and R_1. Dipole shall be shifted along L_1 for maximum output
NOTE:		Similar circuits can be built using an RCA 8012A or 8025A tube.

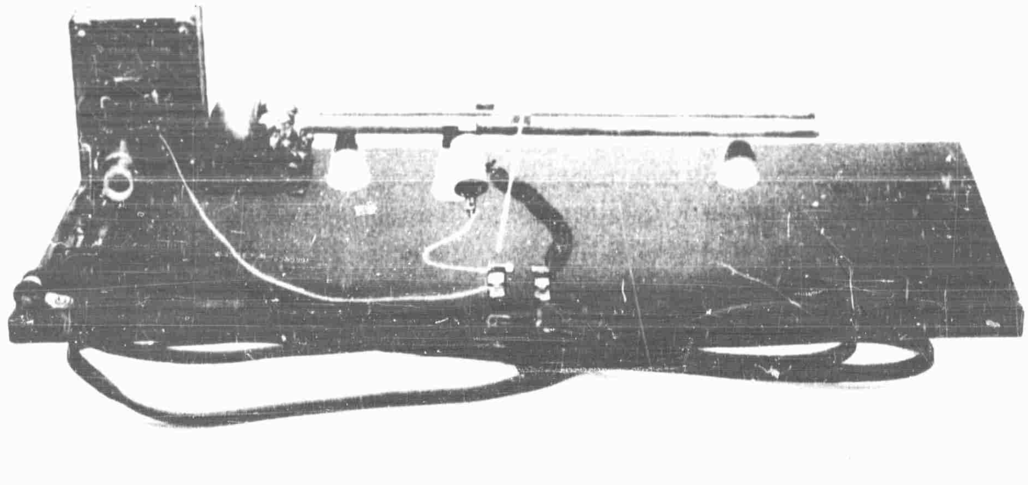


FIGURE 26 - Peak Power Source for Plane Waves at 400 mc

drops to 377 ohms. The wave impedance of magnetic fields is always less than 377 ohms and therefore the curves for magnetic and electric fields could never meet, as such, since the field would be essentially that of plane waves at the meeting point. (Magnetic fields and electric fields predominate for screen room environments only up to about 20 mc.)

Tests of the NADC-AEEL room in the microwave region demonstrated the considerable variation in shielding effectiveness caused by the effect of slight deviations of the nominal 1-inch screen spacing at these frequencies. At 9375 mc, for example, measurements of shielding effectiveness varied from 70 to 130 db for a change in screen spacing of the order of $\lambda/4$. Since the screen spacing could not be maintained precisely, it was purposely varied during the tests to obtain both minimum and maximum shielding effectiveness. (See previous description of test for plane waves at microwave frequencies.) No tests were made of the room at 3000 mc because radar equipment operating at this frequency (e.g., the AN/APS-20) was unavailable during the period of the tests. However, it was considered that sufficient satisfactory data was obtained at 1000 and 10,000 mc to approximate the shielding effectiveness of the room at 3000 mc. The shaded area of figure 8 indicates minimum and maximum shielding effectiveness in the region between 1000 and 10,000 mc and is based on the measurements at 1000 and 10,000 mc and on calculations. Had it been possible to maintain the screen spacing at exactly 1 inch, the shielding effectiveness curve would lie within this area, as indicated, with maximum shielding effectiveness occurring at about 2950 mc, the point where a 1-inch spacing would equal $\lambda/4$. This is illustrated by figure 27 which presents calculated shielding effectiveness data based on an assumed unvarying 1-inch screen spacing.

During the microwave tests one of the standard room panels was temporarily replaced by an experimental panel constructed with 22-mesh, 10-mil screening instead of the regular 22-mesh, 15-mil material. At 9375 mc, the shielding effectiveness of this panel was found to vary from 30 to 80 db. This was in contrast to the 70- to 130-db variation shown by the standard panels at the same frequency and was evidently caused by the higher intrinsic impedance and higher percentage of open area of the substitute screening.

No test of the room was made in the frequency range from 10,000 to 30,000 mc. However, the shielding effectiveness at the latter frequency would necessarily be much lower than 70 db; possibly as low as 25 db. At 30,000 mc, the reflection loss contributed by the screen spacing probably would not amount to more than 30 db and the average over-all shielding effectiveness should therefore run somewhere between 25 and 55 db.* A decrease in shielding effectiveness is to be expected at this frequency since the size of the openings in the screening approaches that of the wavelength. Some decrease also would be attributable to an increase in the impedance of the screening at this frequency.

During the test program it was found necessary to carefully check attenuators and detectors for r-f case leakage (signal pick-up through the case). This concerned operation of these units both inside and outside the screen room. In several instances it was discovered that the pick-up through the case of a unit exceeded that provided by the input. The difficulty was corrected by placing such units inside a shielded copper case (figures 22, 23, and 24).

---

* Where higher values are required, screening must be replaced by solid metal sheets. Sheet metal rooms can theoretically provide a shielding effectiveness of several hundred db at these frequencies, the exact value being impossible to measure because of the limitations imposed by the dielectric strength of air.

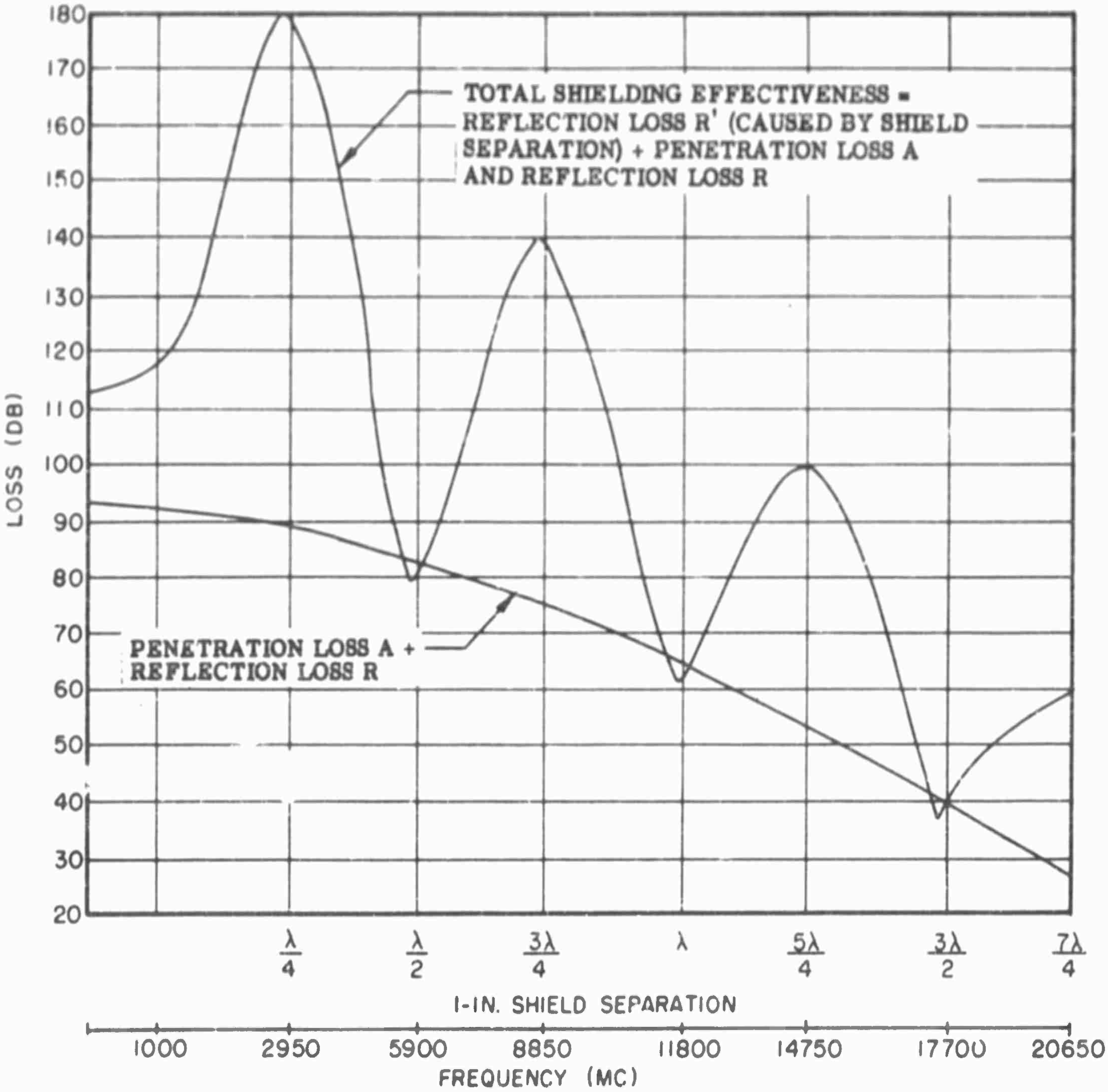


FIGURE 27 - Illustrating the Effect of Shield Separation on Total Shielding Effectiveness

SECTION IV

ESTIMATED COST OF SHIELDED ENCLOSURES AND LIST OF ENCLOSURE SUPPLIERS

ESTIMATED COST

Shielded enclosure costs are determined primarily by the price of the materials involved and the prevailing wages of skilled labor. Enclosure costs can be estimated from the following list which presents typical, current prices of various types of commercial enclosures. The prices include profit and overhead and are based on volume production. If built by the user, the unit cost for any one of these types would probably run 50 percent more.

Type No.	Basic Design and Size	Type of Shielding and Shielding Material	Typical Selling Price
1.	Takedown, cell-type design using 32-in. panels. Enclosure dimensions: 8 by 7 by 16 ft	Double-shield; 22-mesh, 15-mil, copper screening	$2200
2.	Same as Type 1.	Double-shield; each shield of 10-mil, solid sheet copper (or 3-mil "Sisalkraft")*	$2000
3.	Same as Type 1.	Double-shield; one shield of 10-mil, solid sheet copper and one of 10-mil solid sheet iron (galvanized)	$1900
4.	Same dimensions and panelled construction as Type 1, but with single instead of double walls.	Single-shield; 22-mesh, 15-mil, copper screening	$1100
5.	Same as Type 4.	Single-shield; 10-mil, solid sheet copper	$1000

* "Sisalkraft" = heavy tar paper containing 3-mil copper deposit.

The above prices do not include power line filters, test tables, or other accessories. Costs of suitable power line filters are as follows:

Mfr Type (or equivalent)	Electrical Rating	Frequency Range	Typical Selling Price
Hopkins Engineering Co. Type No. 109	100 amp, 500 V	0.014 to 1000 mc	$90
Filtron Company, Inc Type No. FSR-200	50 amp, 250 V	0.014 to 1000 mc	$90
Tobe Deutchmann Corp. Type No. 1180-2	100 amp, 500 V	0.15 to 1000 mc	$70
Tobe Deutchmann Corp. Type No. 1457	100 amp, 500 V	above 1000 mc	$90

NOTE: The above filters can be operated at power frequencies up to 800 cps.

It should be noted that the list of room costs does not include costs for double-shield rooms of isolated-shield construction or costs for non-takedown, integral-unit rooms. Isolated-shield construction increases the cost of takedown-type rooms by about 30 percent and the improvement in shielding effectiveness is negligible where it is most needed, that is, for magnetic fields at frequencies below 1 mc. If constructed by the user, non-takedown rooms (with or without isolated shields) can be constructed at a cost 30 to 50 percent below that of the takedown types. Where such a room is built on the user's premises by an outside contractor, it frequently enters the "custom-built" category and the cost may equal or exceed the cost of commercially-produced standard takedown types.

Referring to the cost list for various types of rooms, it is pointed out that the use of "Sisalkraft" as a substitute material for the 10-mil sheet copper (in room type No. 2) will not appreciably lower the cost. Also, the "Sisalkraft" has less rigidity and puncture resistance and provides less shielding effectiveness.

SUPPLIERS OF SHIELDED ENCLOSURES

Shielded enclosures have been produced commercially since 1948 and at the present time there are several concerns devoted exclusively to the manufacture of this type of equipment. All of these concerns concentrate primarily on production of the basic NADC-AEEL takedown cell-type design. However, several have developed various construction refinements and detail improvements and at least two companies produce solid sheet metal rooms in addition to screen rooms. Some manufacturers will undertake the construction of non-takedown rooms, on special order, and all will supply consulting services to laboratories and industrial plants on shielding and filtering problems.

Advertisements by suppliers of shielded enclosures appear regularly in issues of "Electronics," "The Proceedings of the I.R.E.," "Electrical Equipment," etc. Some of the known suppliers include the following:

1. Ace Engineering and Machine Company, Inc., Philadelphia, Pa.
2. Ark Engineering Company, Philadelphia, Pa.
3. Electro-Search, Philadelphia, Pa.
4. General Laboratory Associates, Inc., Norwich, N. Y.
5. Erick A. Lindgren and Associates, Chicago, Ill.
6. Rodman H. Martin Company, Inc., Philadelphia, Pa.
7. Shielding Incorporated, Riverside Park, N. J.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions are based on the theory and design considerations, the developments, and the tests and evaluations associated with this project.

Theory and Design

1. Fundamental shielding theory is based on an analysis which considers two current filaments encased in a cylindrical shield (or a point source at the center of a spherical shield) surrounded by free-space conditions. However, this analysis also provides a satisfactory approximation for use in determining the shielding effectiveness offered by plane-surface shields under limited free-space conditions. The theoretical calculations, correction factors, and tables presented in this report provide a reasonable reconciliation between theoretical and practical considerations and make it possible to predict maximum shielding effectiveness for various shielding materials and enclosure designs.

2. The shielding effectiveness of a shielded enclosure is a variable quantity that depends on numerous factors such as:

a. Type of field.

b. Wave impedance.

c. Signal source-to-shield distance.

d. Type of shielding material, its thickness, and percentage of open area (this latter factor applies to screening material and perforated metal sheet).

e. Enclosure type (single-shield, double-shield cell-type, or isolated double-shield).

f. Shield separation (applies to double-shield enclosures).

3. In general, the necessary steps for estimating the shielding effectiveness of an enclosure by means of the theoretical calculations and tables of this report are as follows:

a. Consider the test frequency f.

b. Determine the relative conductivity G and the relative permeability μ of the shielding material.

c. Calculate the penetration loss A.

d. Calculate the intrinsic impedance of the shielding material Z_S.

e. Calculate the wave impedance of the field Z_W for electric fields, magnetic fields, and plane waves.

f. Calculate the reflection loss R.

g. Apply correction factor B when $A < 10$ db.

h. If spaced double shields are used, calculate the added reflection loss R' caused by the shield separation.

i. The total shielding effectiveness S of the enclosure will be expressed by $S = R + A + B + R'$ in db.

4. Penetration loss should not be regarded as the only factor contributing to shielding effectiveness. In some instances penetration loss may be equalled or even exceeded by the reflection losses occurring at each surface of a shield. (It should be remembered, however, that reflection loss values require correction by application of the B factor if the shield's penetration loss is less than 10 db.) Penetration loss decreases for solid metal barriers as the frequency decreases and is independent of the type of field involved. On the other hand, reflection loss may either decrease or increase with frequency depending on the type of field involved. Reflection loss decreases for magnetic fields as the frequency decreases. For electric fields and plane waves, reflection loss increases as the frequency decreases.

5. Except for magnetic fields at low frequencies, shield separation considerably increases the over-all shielding effectiveness of double-shield enclosures. This is based on the theoretical analysis of the effect of shield separation developed under this project and presented in section I of this report. It is felt that the NADC analysis, which considers the space between shields as a discontinuity in a transmission line and uses transmission line formulas for determining the insertion loss, provides a satisfactory means of evaluating shield separation in instances where the shielding material is solid (unperforated) metal with a penetration loss of over 10 db. Satisfactory experimental proof of this was considered obtained for plane waves at microwave frequencies and there is no reason to doubt the validity of the analysis for plane waves at lower frequencies and for electric fields. However, proof of the validity of the analysis remains to be made for low-frequency magnetic fields (below 1 mc for copper and below 12 mc for iron). Also, further work is needed to produce a theoretical analysis and a formula for determining the effect of shield separation for solid shields of less than 10 db penetration loss per shield and for screening material.

6. Where a wide range of frequencies is involved, increasing the shield separation for double-shield enclosures from the standard 1-inch spacing to 4 inches will not materially improve the shielding effectiveness.

7. Theoretically (as shown in the text), for various fields and frequencies, a comparison of the effect of shield separation in double-shield enclosures of cell-type construction and those of isolated-shield construction (both types constructed of solid shields affording greater than 10 db penetration loss per shield and utilizing 1-inch shield separation) will show the shielding effectiveness characteristics indicated below:

a. Magnetic Fields - Shield separation in both types contributes very little to over-all shielding effectiveness in the case of magnetic fields at low frequencies (below 1 mc for copper and below 12 mc for iron). The double shields of cell-type enclosures are effectively connected together to form a single shield at these frequencies, because

the panel width is negligible in comparison with the wavelength. Consequently, a cell-type enclosure should provide shielding effectiveness comparable to that of a single-shield enclosure constructed of shielding material of twice the gauge. On the other hand, the double shields of an isolated-shield enclosure are not connected at any point and theoretical considerations indicate that the shielding effectiveness realized may be about 3 db below that provided by cell-types.

b. Electric Fields and Plane Waves - Shield separation contributes considerably more to over-all shielding effectiveness for isolated-shield enclosures than for cell-type enclosure for electric fields and plane waves in the region below approximately 20 mc and, to a lesser extent, above 20 mc. In this respect, isolated-shield construction is superior to cell-type construction. However, the superiority of isolated-shield construction in this region is somewhat superfluous since generally adequate shielding effectiveness against these fields is provided by either type through penetration and reflection loss regardless of shield separation. The shields of cell-type enclosures become increasingly isolated with an increase in frequency and performance differences between the two types of construction therefore tend to disappear at the higher frequencies.

c. Plane Waves at Microwave Frequencies - At microwave frequencies, the effect of shield separation for a cell-type enclosure is essentially the same as that for an isolated-shield type; the cell-type enclosure shields become effectively isolated when the width of each panel section (cell) becomes much larger than the wavelength. At these frequencies there is a considerable increase in shielding effectiveness (as much as 50 db) when the spacing of the shields becomes an odd multiple of $\lambda/4$ and a slight decrease of -3 db when the spacing becomes a multiple of $\lambda/2$.

8. Inside a shielded enclosure, regardless of the type of design used, reflections will always be present and the enclosure may become a cavity resonator at several frequencies. Measurements made of an electromagnetic field inside an enclosure will vary greatly because of the presence of reflections and standing waves. Such measurements cannot be easily correlated with measurements made under free space conditions. In order to obtain meaningful and repeatable results, it will be necessary to place the pick-up antenna in such a position as to record the maximum induced voltage. Reflections and standing waves at any one frequency can be minimized by the use of absorbing materials and by changing the shape and size of the enclosure.

Construction

1. Single-shield enclosures are inferior to double-shield enclosures for most general purpose applications. Double-shield enclosures, in addition to offering extra shielding effectiveness through the shield-separation effect, also offer extra protection from leakage in the event that one of the shields is accidentally punctured.

2. The joints and seams in the shielding material of a shielded enclosure are the most critical areas of possible r-f leakage. Regardless of the type of construction used, the shielding effectiveness characteristics of an enclosure will largely depend on how low an r-f impedance bond is present at the joints and seams.

3. Permanently-constructed non-takedown enclosures are the most difficult type to construct because of the problem of achieving adequate joints and seams; this is particularly true for enclosures constructed of solid sheets. Such enclosures can be constructed properly only by skilled personnel. Joints and seams of the completed enclosure are usually

not accessible for inspection, cleaning, or repair. Once constructed, enclosures of this type cannot be moved successfully to a new location. Similarly, permanently-constructed enclosures cannot be torn down and rebuilt successfully. Early obsolescence is generally unavoidable with this type of enclosure.

4. Takedown-type enclosures can provide effective low r-f impedance bonds at all panel joints and (after the component panels have been precision fabricated) can be assembled, disassembled, and serviced by relatively untrained personnel. Panel joints are readily accessible for inspection, cleaning, and repair. Takedown enclosures can be disassembled and reassembled in a new location as the occasion demands.

5. Double-shield takedown enclosures of cell-type construction are simpler to build and require less material (framework members, bolts, pressure plates, etc.) than those of isolated-shield construction.

6. In general, present laboratory and industrial requirements for shielded enclosures are adequately met by takedown cell-type screen rooms constructed in accordance with the NADC-AEEL basic design. The NADC-AEEL room provides an average shielding effectiveness of 100 db from 150 kc to 10,000 mc. At 200 kc, in the most severe cases of magnetic fields, the shielding effectiveness averages around 70 db and shielding effectiveness varies between 70 db and 130 db at 10,000 mc. Above 10,000 mc, however, shielding effectiveness falls rapidly to below 50 db. Rooms of this type possess the following advantages:

a. They can be assembled quickly by relatively untrained personnel.

b. They can be disassembled readily for inspection, cleaning, repairs, relocation, or storage.

c. They can be made larger or smaller by the addition or subtraction of the proper number of panels.

d. They can be adapted to include special services such as forced-air ventilation (through waveguide-type attenuators), externally-powered drive shafting, etc.

Materials

1. Panel Framework Material

a. Wood is the most satisfactory material for the panel framework of takedown-type enclosures. The resiliency of wood frames contributes considerably to the achievement of low r-f impedance bonds at joints between panels by distributing assembly-bolt pressures and affording misalignment takeup.

b. Metal frames are not practical in their present state of development. Metal frames possess little or no resiliency and low r-f impedance bonds between panels of an assembled enclosure are very difficult to achieve, even with panels individually fabricated to extremely close tolerances.

2. Shielding Material

a. Screening material approaches the shielding effectiveness of solid metal sheets as the frequency is lowered and as the open area of the screening is reduced. The 22-mesh, 15-mil, copper screening specified for the NADC-AEEL screen room represents

a compromise choice based on maximum shielding effectiveness, maximum frequency range, and maximum utility. Screening of finer mesh (of either copper or galvanized iron wire) will increase shielding effectiveness at all frequencies, but the fine mesh will tend to make the room airtight and a forced-air ventilation system will be required as in the case of sheet metal rooms. Screening of coarser mesh will reduce the room's shielding effectiveness, especially at high frequencies.

b. In general, screening material provides a fairly high percentage of penetration loss. As in the case of solid sheet material, screening must provide penetration loss in order to provide reflection loss.

c. Galvanized iron screening (hardware cloth) provides a little more shielding effectiveness than copper screening at low frequencies, but less shielding effectiveness than copper at microwave frequencies.

d. A double-shield enclosure of 22-mesh, 15-mil, copper screening cannot provide 100-db shielding effectiveness for frequencies as high as 30,000 mc. For these frequencies, solid sheet material of adequate thickness must be used.

e. A double-shield enclosure of 22-mesh, 15-mil, copper screening cannot provide 100-db shielding effectiveness for the most severe case of magnetic fields at frequencies as low as 10 kc. Solid iron sheet of adequate thickness should be used for these conditions.

f. Heavy single shields of solid metal (e.g., 300-mil, $\mu = 1000$, iron, 81-mil Mumetal, 79-mil Permalloy, or 56-mil Hipernik) are necessary to provide 100-db shielding effectiveness for severe cases of magnetic fields at 60 cps. Shields of this type will also provide 100-db shielding effectiveness for the higher frequencies up to and beyond 30,000 mc.

g. For small enclosures, the psychological factor of claustrophobia should be taken into account when choosing between screened types and those constructed of solid sheet material. Occupants of sheet metal enclosures may be affected by claustrophobia since the solid shields cut off visual and acoustical contact with the outside.

3. Power Line Filters

a. The choice of proper power line filters to meet the shielding effectiveness requirements for any given shielded enclosure is a separate consideration from that of the enclosure itself and can be determined after the enclosure design parameters have been worked out.

b. Power line filters are commercially available for most attenuation needs. For special cases, existing commercial types can be used in various combinations or can be modified to suit.

Enclosure Costs

1. If constructed by the user, non-takedown enclosures cost approximately 30 to 50 percent less than the takedown types. However, the freedom from early obsolescence of the takedown enclosures, plus their greater utility and adaptability, more than compensates for their higher initial cost.

2. Double-shield enclosures of cell-type construction cost considerably less than isolated-shield types and adequately meet the normal shielding requirements of industrial plants and laboratories.

Test Methods

1. Significant testing for shielding effectiveness demands the recognition and careful control of all factors influencing the test setup, regardless of the test method employed.

2. The insertion-loss test method developed under this project provides for maximum control of existing test conditions and makes for repeatable results in repeated tests. The method is equally valid for measurements of ratios of real powers, apparent powers, voltages, or currents. For production testing of enclosures of identical design and construction, the insertion-loss method can be confined to a test for magnetic fields at a single spot frequency of 200 kc. (Magnetic fields in this region provide the most severe test for shielded enclosures.)

3. The so-called "attenuation method" of testing shielding effectiveness is not recommended because its several uncontrolled variables can lead to different results depending upon whether a ratio of real powers, apparent powers, voltages, or currents is being measured.

4. The surface transfer impedance method is not recommended because it evaluates penetration loss alone and applies only over a limited frequency range.

Enclosure Specifications

1. Design, construction, and test specifications for shielded enclosures should be based on a fundamental enclosure design that has been subjected to an extensive test and evaluation program over a period of years.

2. Widespread adoption of the NADC-AEEL Takedown Cell-Type Screen Room by government agencies and private industry, together with volume production of the room by several manufacturers, qualifies the basic design for consideration as the primary standard in the preparation of shielded enclosure specifications. Over 1000 of these rooms are now in use throughout the country.

3. In the absence of other acceptable methods for determining shielding effectiveness, the detailed insertion-loss test method developed under this project merits primary consideration for use in shielded enclosure test specifications.

RECOMMENDATIONS

1. Adopt the basic design and construction of the NADC-AEEL Takedown Cell-Type Screen Room as a military standard for use in evaluating shielded enclosures and screen rooms. Regardless of initial performance, reserve approval of any other design as the standard until it has been extensively tested and evaluated over a period of years.

2. Adopt the NADC-AEEL detailed insertion-loss method for determining shielding effectiveness as the basis for a military standard.

3. Approve proposed Specification No. MIL-S-4957(Aer), based on the results obtained under this project, for use in the procurement of shielded enclosures and screen rooms and recommend its adoption by the military services.

4. In a further study of shielded enclosures the following should be investigated:

a. Develop practical formulas for screening material to give the intrinsic impedance and thickness of an equivalent solid metal barrier that would provide the same shielding effectiveness as the screening. The shielding effectiveness of the equivalent barrier then could be calculated by means of the basic formulas of this report.

b. Develop a formula for use in calculating the effect of shield separation for double shields affording less than 10 db penetration loss per shield; experimentally compare the over-all shielding effectiveness produced by two such separated shields of a given shield thickness with that produced by a single shield of twice the thickness.

c. Experimentally determine the differences in shielding effectiveness between double-shield enclosures of cell-type construction and those of isolated-shield construction in order to obtain a check for the theoretical analysis presented in this report. The experiments should test both sheet metal and screened enclosures.

d. Investigate the possibility of reducing to a minimum the reflections and resonances inside an enclosure by changing the enclosure shape and size, and by lining the enclosure interior with absorbing materials.

e. Measure the shielding effectiveness of cell-type shielded enclosures at distinct frequencies where the width or length of a single panel (or the width, length, or height of the entire enclosure) becomes an odd multiple of a quarter wave, or a multiple of a half wave. These tests are considered necessary to determine if there are any pronounced changes in the shielding effectiveness similar to the changes found at microwaves due to the distance separating the inner and outer shields.

ACKNOWLEDGEMENTS

The author wishes to express his indebtedness to Messrs. C. Johnson and William Jarva for their assistance in the preparation of the theoretical analysis, the development of the measuring techniques, and the design of the shielded enclosures used in this project.

Considerable credit is given to Mr. Charles M. Crocker of the AEEL Technical Publications Branch for technical editing of the manuscript.

REFERENCES AND BIBLIOGRAPHY

(a) BUAER ltr Aer-EL-52 ser 22172 of 24 Mar 1949
(b) "Specification and Design Characteristics for ARRL Screen Room Model 1A & 1B," C. S. Vasaka, NADC-ARRL Report No. 5-48, 11 Aug 1947
(c) "Shielding for Diathermy," W. C. Stoker and W. W. Seifert, Rensselaer Polytechnic Institute, FCC Docket No. 6651, Contract No. OEMsr-225, Project C-31, 29 Oct 1943
(d) "Electromagnetic Waves," S. A. Schelkunoff, D. Van Nostrand Co., Inc., 1943
(e) "Microwave Transmission," J. C. Slater, McGraw-Hill Book Co. Inc., 1942
(f) "Study of Tubular Shielding and Development of Flexible Shield-Conduit," A. R. Anderson, The American Brass Company and Technicraft Laboratories Inc., Final Report - Vol II, Contract NOa(s)-8098, 29 Jun 1949
(g) "Radio Engineer's Handbook," F. E. Terman, McGraw-Hill Book Co. Inc., 1943
(h) "Principles Governing the Construction of Shielded Rooms," M. T. Jones, Standford Research Institute Technical Report No. 1, U.S. Navy Bureau of Yards and Docks Contract No. NOy 22272, 12 Apr 1951
(i) "Principles of Microwave Circuits," C. G. Montgomery, R. H. Dicke, and E. M. Purcell, M.I.T. Radiation Laboratory Series, Vol No. 8, McGraw-Hill Book Co. Inc., 1948
(j) "Magnetic Materials at Radio Frequencies," F. M. Colebrook, Great Britain, Department of Scientific and Industrial Research and Radio Research Board, Report No. 14
(k) "Design Techniques for Interference-Free Operation of Airborne Electronic Equipment," USAF Contract No. AF 33(038)23341, 1952
(l) "Elimination of Radio Interference in Aircraft," Bureau of Aeronautics, NAVAER 16-5Q-517, 1 Mar 1946
(m) "Gratings and Screens as Microwave Reflectors," W. D. Hayes, M.I.T. Radiation Laboratory Report No. 54-20, 1 Apr 1943
(n) "Measuring the Shielding Efficiency of Screened Enclosures," H. E. Dinger and J. E. Raudenbush, Naval Research Laboratory Report No. 3908, 14 Nov 1951
(o) "Notes on Design, Construction and Evaluation of Shielded Rooms," G. A. Morgan, Naval Research Laboratory Report No. 3578, 9 Dec 1949
(p) "Enclosure, Electromagnetic Shielding, Portable, Prefabricated, For Electronic Test Purposes," Military Specification MIL-S-4957(Aer)
(q) "Preliminary Service Manual for NADC-AEEL Takedown Cell-Type Screen Room," C. S. Vasaka, NADC Report No. NADC-EL-54122, 2 Dec 1954
(r) "Evaluation of Seams and Gaskets Used in Shielding Enclosures, and Development of Correctives for Improvement" W. E. Stinger, NADC Report No. NADC-EL-52139, 3 Feb 1953
(s) "Electromagnetic Theory," J. A. Stratton, McGraw-Hill Book Co.Inc., 1941
(t) "Fields and Waves in Radio," S. Ramo and J. R. Whinnery, John Wiley and Sons, 1944
(u) "The Technique of Radio Design," E. E. Zepler, Chapman and Hall, Ltd., Chapter 8, pp 183-205
(v) "Some Theoretical Studies of the Effectiveness of a Rectangular Shield to Electromagnetic Waves Generated by a Pair of Parallel Current Filaments," R. B. Shulz, University of Pennsylvania, Jun 1951

(w) "Cylindrical Shielding and its Measurement at Radio Frequencies," A. R. Anderson, Proc. I. R. E., Vol 34, No. 5, pp 312-322, May 1946

(x) "Effectiveness of Conduit as R-F Shielding," S. L. Shive, Electronics, Vol 19, No. 2, pp 160-166, Feb 1946

(y) "Attenuation of Electromagnetic Fields in Pipes Smaller Than the Critical Size," E. G. Linder, RCA Review, pp 355-361, 1948

(z) "Experiments on Electromagnetic Shielding at Frequencies Between One and Thirty Kilocycles," W. Lyons, Proc. I. R. E., Vol 21, p 574, Apr 1933

(aa) "The Evaluation of a Sectionalized Shielded Enclosure," L. Castriota, H. Vasques, and L. Schwartz, Polytechnic Institute of Brooklyn, Report No. R-275-52, PIB-214, USAF Contract No. AF-28(099)-8, 11 Jul 1952

(bb) "A Theoretical Investigation of Electromagnetic Shielding," D. B. Wright and C. R. Freberg, Naval Civil Engineering Laboratory Technical Report No. 006, 10 Nov 1949

(cc) "Attenuation Tests on Screened Rooms," J. J. MacGregor, E. B. McIntyre, and G. F. Wall, Naval Research Laboratory Report on Problem A211T-R, 29 Oct 1946

(dd) "An Investigation into the Use of Aluminum and Other Metals for Shielded Rooms," A. M. Intrator, and C. R. Freberg, Naval Civil Engineering Laboratory Technical Report No. 007, 21 Nov 1949

(ee) "Semi-Portable Screened Booths," Naval Research Laboratory Drawing No. 10F916A, Feb 1947

(ff) "A Double Screen Room With a Novel Method of Closure," A. L. Weisbecker, University of Pennsylvania, U. S. Navy Bureau of Ships Contract No. NObs-25397, 10 Apr 1946

(gg) "Elimination of Radio Interference by Shielding and Design of Shielded Rooms," D. L. Benedict, Stanford Research Institute Final Report SRI Project No. 336, U. S. Navy Bureau of Yards and Docks Contract No. NOy-22272, Aug 1952

(hh) "Design of a Welded Steel Shielded Room," M. A. Intrator, Naval Civil Engineering Laboratory Technical Memorandum No. M-046, Project NY411002-1, 15 Sep 1951

(ii) "Shielding of Dielectric Heating Installations," G. E. Klingman and G. H. Williams, Electronics, Vol 8, No. 5, pp 106-109, May 1945

(jj) "Radiation from R-F Heating Generators," A. G. Swan, Electronics, Vol 19, No. 5, pp 162-170, May 1946

(kk) "Shielding Experiments and TVI," M. Seybold, CQ, Vol 5, No. 6, pp 31-34, Jun 1949

(ll) "Screened Testing Booths," Wireless World, Vol 51, No. 4, pp 116-117, Apr 1945

(mm) "The Design of a Screened Room," C. C. Eaglesfield, Electrical Engineering, Vol 18, No. 2, pp 106-108, Apr 1946

(nn) "Construction of a Shielded Room in VHF Field," C. R. Pine, Electronics, Vol 21, No. 4, pp 150-158, Apr 1, 1948

(oo) "Interference from Industrial R-F Equipment - Performance of Screening Rooms," J. Miedzinski and S. F. Pearce, The British Electrical and Allied Industries Research Association, Reference M/T104, 1 Mar 1949

(pp) "Shielding HF Interference," A. F. Murray, Electronic Industries, Vol 4, No. 8, pp 108-110, 142, 146, Aug 1945

(qq) "The Performance of Screening Rooms," J. Miedzinski and S. F. Pearce, Electronic Engineering, pp 414-419, Oct 1950

(rr) "Investigations of the Measurement of Noise," University of Pennsylvania Progress Report No. 20, Navy Contract NObsr-49128, 15 Apr 1951

(ss) "Notes on the Construction of Semi-Portable Screened Booths," A. E. Craig, Naval Research Laboratory Report No. 3920-144/48, LLC, 12 Jul 1948

(tt) "A Technique for Measuring the Effectiveness of Various Shielding Materials," H. E. Dinger and J. E. Raudenbush, Naval Research Laboratory Report No. 4103, 22 Jan 1953

CORRECTIONS AND ADDITIONS

The research and investigation phases of the project involved extensive use and analysis of the shielding literature included in the above list. As a result of this, it is believed that four of the references require corrections or additions as indicated below:

Reference and Page Number	Equation or Expression	Correction or Addition
Ref (f), p 18	Wave impedance Z_1 and Z_2	Indicate that Z_1 and Z_2 are expressed in vector form
Ref (f), p 36	Equation (50a)	Change $-2\ t'$ to $-2(\alpha + j\beta)t'$ to correspond to equation (23) of this present report.
Ref (f), p 36	Equation $M = \left[\frac{1-\lvert k\rvert}{1+\lvert k\rvert}\right]^2$	Change to $M = \left[\left\lvert\frac{1+k}{1-k}\right\rvert\right]^2$
Ref (h), p 10	Equation (12)	Change the second term to correspond to equation (25) of this present report.
Ref (k), p VIII-3 of Appendix VIII	Equation (2)	Change the second term to correspond to equation (25) of this present report.
Ref (rr), pp 10 and 12	Equations 1, 2, 3, and 4	Include the B factor as given in equation (25) of this present report.

REFERENCES AND BIBLIOGRAPHY CLASSIFIED ACCORDING TO SUBJECT

The shielding literature included in the previous list of references concerns the following 14 subject categories:

1. <u>Basic Theory of Shielding and Transmission of Electromagnetic Waves</u>

   References: (d), (e), (f), (g), (s), (t), (u), (v).

2. <u>Transmission Line Theory</u>

   References: (e), (g).

3. Theory of Shielding as Applied to Shielded Enclosures

References: (c), (f), (h), (k), (l), (n), (o), (u), (x), (bb).

4. Methods of Measuring Shielding Effectiveness

References: (b), (c), (f), (n), (o), (p), (w), (x), (aa), (cc), (kk), (oo), (rr), (tt).

5. Surface Transfer Impedance Method of Measuring Shielding Effectiveness

References: (f), (n), (w).

6. Shielding of Metallic Conduits

References: (f), (l), (w), (x), (y).

7. Shielding for R-F Heating Generators

References: (c), (ii), (jj), (oo).

8. Shielding for Frequencies from 1 to 30 kc

Reference: (z).

9. Characteristics of Metallic Screening Materials

References: (m), (oo), (qq).

10. Characteristics of Metals at Microwave Frequencies

References: (h), (i), (j), (k), (l).

11. Permeability and Conductivity of Metals

References: (h), (j), (hh).

12. Construction Details of Shielded Enclosures

References: (b), (c), (k), (l), (n), (o), (r), (cc), (dd), (ee), (ff), (gg), (hh), (ll), (mm), (nn), (pp), (ss).

13. Construction Details of Cell-Type Shielded Enclosures

References: (b), (c), (p), (q).

14. Estimated Cost of Shielded Enclosures

References: (c), (hh).

APPENDIX

PRELIMINARY SERVICE MANUAL

FOR

NADC-AEEL TAKEDOWN CELL-TYPE SCREEN ROOM

(Report No. NADC-EL-54122)

TABLE OF CONTENTS

GENERAL DESCRIPTION

PURPOSE OF MANUAL

This manual describes the assembly, disassembly, testing, and maintenance of the NADC-AEEL Takedown Cell-Type Screen Room developed by the Aeronautical Electronic and Electrical Laboratory of the U. S. Naval Air Development Center, Johnsville, Pennsylvania. Much of the information presented is generally applicable to any type of shielding enclosure.

PURPOSE OF EQUIPMENT

The NADC-AEEL Takedown Cell-Type Screen Room is an improved type of shielding enclosure for the suppression of r-f interference. The room affords a nominal 100 db of shielding effectiveness over a frequency range from 0.15 to 10,000 mc. This reduction of 100,000-to-1 is sufficient to decrease an area background of 100,000 microvolts per meter to 1 microvolt per meter, the tolerable maximum for testing modern electronic equipment. The room is intended for use in operating, testing, and evaluating sensitive electrical and electronic equipment and can also be used as a screened compartment for isolating equipment which would otherwise cause serious radio and television interference.

CONSTRUCTION

The room is comprised of a series of prefabricated, double-screened, cell-type panels which are bolted together to form the walls, ceiling, and floor. An r-f leakproof door and doorframe are included, and plywood flooring is provided as an overlay for the floor panels.

In the manufacture of a typical panel, two braced rectangular frames are constructed of seasoned pine lumber. One frame is made from 1- by 2-inch material and the other from 1- by 1-inch material. Next, each frame is faced on one side with a piece of 22-mesh, 15-mil copper screening whose length and width dimensions are slightly larger than the frame. The frames are then fastened together permanently, with the screened side of one in contact with the wood framework side of the other. The composite panel thus formed has one outside screened surface, an inner screened surface, and a final outside surface of exposed wood framework. The outer edges of both screens still extend beyond the edges of the composite panel frame, and these are folded over in the final stages of the fabrication process to form an electrically-bonded, 2-ply overlap on the frame periphery. This transforms the double-screened panel into a 6-sided, integral, screened cell.

The exposed wood-framework sides of the panels appear on all outside surfaces of the completed room. The framework contains holes for bolting the panels together and also aids in protecting the panel screens against accidental damage. Room construction details are illustrated in figures 1 through 9.

DESIGN FEATURES

The takedown feature of the room permits quick and easy assembly and disassembly by relatively untrained personnel and makes for minimum storage and transportation space requirements. The length of the room may be varied readily by adding or subtracting the proper number of wall, ceiling and floor panels.

Cell-type construction for screen rooms was originally reported by Rensselaer Polytechnic Institute. The NADC-AEEL cell-type room design is the result of a 4-year development program which produced numerous improvements and new features including the following:

1. Pressure plates under panel mounting-bolt heads and nuts to improve pressure distribution between panels for lower r-f impedance bonds.

2. Provision for bolting floor panels together from inside the room.

3. A completely redesigned door with r-f leakproof seam construction.

4. Power-line filter improvements including higher attenuation, effective input and output decoupling, and improved bonding and installation methods.

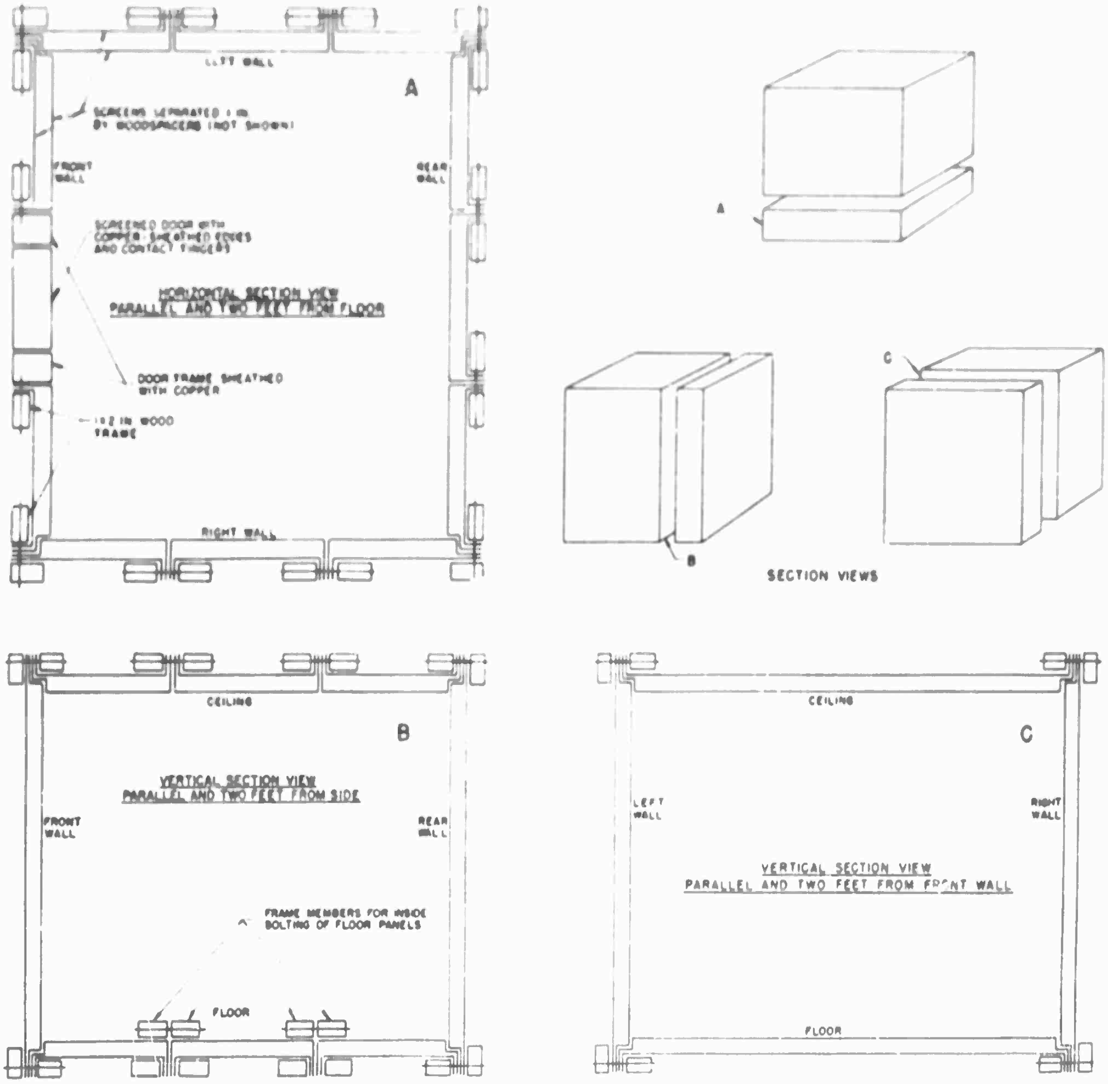


FIGURE 1 - Diagrammatic Illustration Showing Panel and Screen Arrangement of NADC-AEEL Takedown Cell-Type Screen Room

5. Transmission line connectors.

6. Provision for entry of room services such as water, gas, air, and rotating-shaft motive power.

7. Waveguide-type attenuators as room entrances for nonmetallic service lines and forced-air ventilation.

ASSEMBLY AND DISASSEMBLY

GENERAL

The NADC-AEEL Takedown Cell-Type Screen Room is sturdy enough to give long, continuous service and can be assembled and disassembled as occasion demands. However, certain handling precautions must be observed and certain maintenance operations performed to retain maximum efficiency. It should be noted that cursory visual inspection of the room will not necessarily reveal damage productive of excessive r-f leakage.

ASSEMBLY

Handling of Panels - Panels must be handled with care at all times to prevent damage to the screening material. The screened surface of one panel should be placed in contact with the wood framework surface of an adjacent panel whenever panels are stacked together.

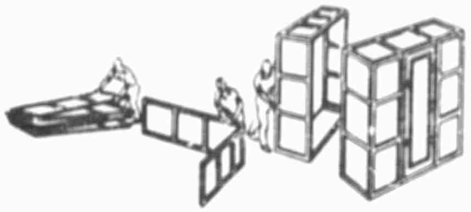
Erection Sequence - Two suggested methods for erecting the room are indicated in figure 2 (a) and (b). The erection sequence for the first method is as follows:

1. Floor panels and plywood flooring
2. Test tables
3. Wall panels
4. Door and door frame
5. Ceiling panels
6. Power line filters
7. Room equipment

The second method permits construction of the room from a series of assembled transverse sections each comprised of a floor panel, a ceiling panel, and two wall panels. End-wall panels are bolted to two of these sections, one of which includes the door panel,

and the room is completed by the insertion of the proper number of intermediate sections. The room can be lengthened or shortened by the addition or subtraction of one or more of these sections.

(a) FLOOR, WALLS, AND CEILING SEQUENCE



(b) ASSEMBLED TRANSVERSE-SECTION SEQUENCE

FIGURE 2 - Screen Room Erection Methods

Ceiling Erection - When the screen room is erected in accordance with the floor, walls, and ceiling sequence, it is important that the bolts joining the wall panels be left loose to allow insertion of the ceiling panels. The bolting of ceiling panels along their long dimensions should be reserved for the final operation of the assembly process regardless of the erection method used. A sturdy plank should be bridged across the top of the room to support the weight of workmen performing this final bolting operation. Do not attempt to stand, walk, or store equipment on the top of an assembled screen room.

Pressure Plates - Pressure plates must be used under all mounting bolt heads and nuts. The plates provide the necessary pressure distribution for maintaining adequate metal-to-metal contact between panels and prevent serious indenting of the wood of the panel frames. Pressure plates should be purchased for rooms not so equipped. These are available from several manufacturers of screen rooms and can be obtained in sets listed as "Bolts, Pressure Plates, and Lockwashers," from Ace Engineering and Machine Company, Incorporated, Philadelphia, Pennsylvania; and from Shielding Incorporated, Riverside, New Jersey. When ordering, it is necessary to indicate the over-all outside dimensions of the room and the number of component panels.

Bolt Tightening - Because bolt heads and nuts are located close to the panel screens, it is important that wrenches of the proper size and shape be used so as not to damage the screening material. Correct tightening pressure is 140 inch-pounds and should be checked with a torque wrench.

Grounding of Test Tables - The ground plane for the test table (or tables) inside the screen room should be a copper sheet not less than 20 mils thick, not less than 30 inches wide, and not less than 16 square feet in area. (See figures 3 and 4.) It should be bonded to the screening material of the wall panels approximately every 3 feet and at each end. Bonding can be simplified by bending up an edge of the copper sheet to form a vertical flange at the rear of the test table to make contact with the panel screens. Bonding can then be effected at the prescribed 3-foot intervals by drilling clearance holes in the flange to accommodate wood screws which will pierce the screening material and anchor in the wood of the panel framework or cross bracing.

Bonding - A good bond is a metal-to-metal connection having the lowest possible r-f impedance. It is pointed out that the measurement of the d-c resistance of the bond will

not give a satisfactory indication of its r-f impedance magnitude. The best bond between two metallic surfaces can be obtained by using clean metal-to-metal contact under sufficient pressure. Pressure can be applied mechanically in various ways using nuts and bolts, machine screws, self-tapping sheet metal screws, and (where wood backing is present) wood screws. Soldering also may be used, but it is essential that the two mating surfaces be tinned before sweating.

Bonding jumpers are required if the two metallic surfaces to be bonded are physically separated and cannot be brought in direct contact. Jumpers should be made from copper sheet of at least 10 mils thickness and should be as short as possible. Jumper width-to-length ratio should not be less than one to five.

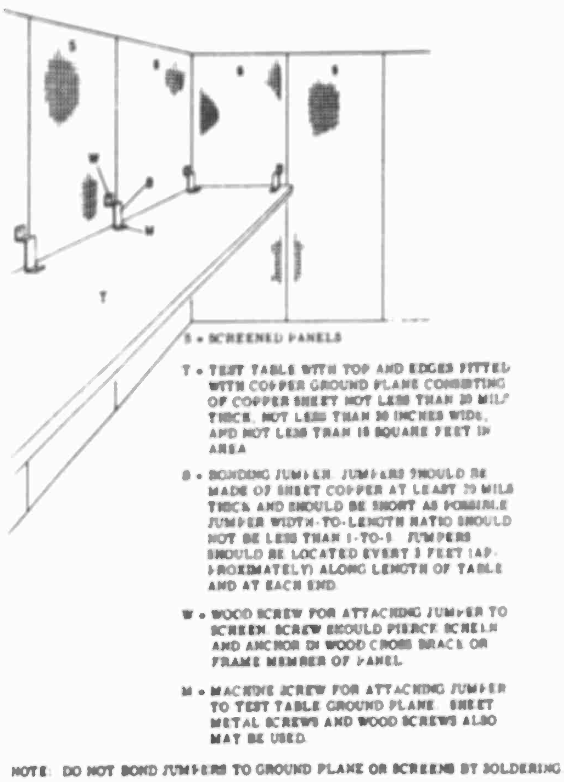


FIGURE 3 - Bonding Test Table to Panel Screens

Any machine screw, wood screw, metallic rod, pipe, etc., that penetrates the panel screen material should be bonded to the screen at the point of penetration. Good bonding must be achieved at these points or severe r-f leakage may develop and lower the shielding effectiveness of the room considerably. Several satisfactory bonding methods are shown in figure 5. Sections (b), (c), and (d) of this figure make use of a metal plate which is soldered to the panel screen. These plates can be made of either brass or copper. They should be at least 2 inches square and of sufficient thickness to contain threads for machine screws, threaded transmission-line barrels, etc. The plates can be soldered to the screen material anywhere on the panel but it is desirable to locate them where the wood backing of a panel cross brace or frame member will afford added support. Additional anchorage strength and rigidity can be gained by including holes in the plates for plate-mounting wood screws.

Soldering to panel screens should be done with an iron (a 300-watt iron is satisfactory). Never use a soldering torch because the open flame will damage the screen wires. Use rosin-core solder or wire solder and an alcohol-rosin flux. Never use acid or salt-content flux.

Reference Ground - The screening material and the test table on the inside of the room are considered as the common r-f reference ground. Although it is not necessary to connect this ground to an outside ground or earth, it is desirable to do so as a safety measure. A water pipe or a steel beam outside the screen room will provide a good ground for this purpose and the standard room design includes a common ground stud on the power line filter panel for an external ground wire connection. Ground wire, size and length are not critical.

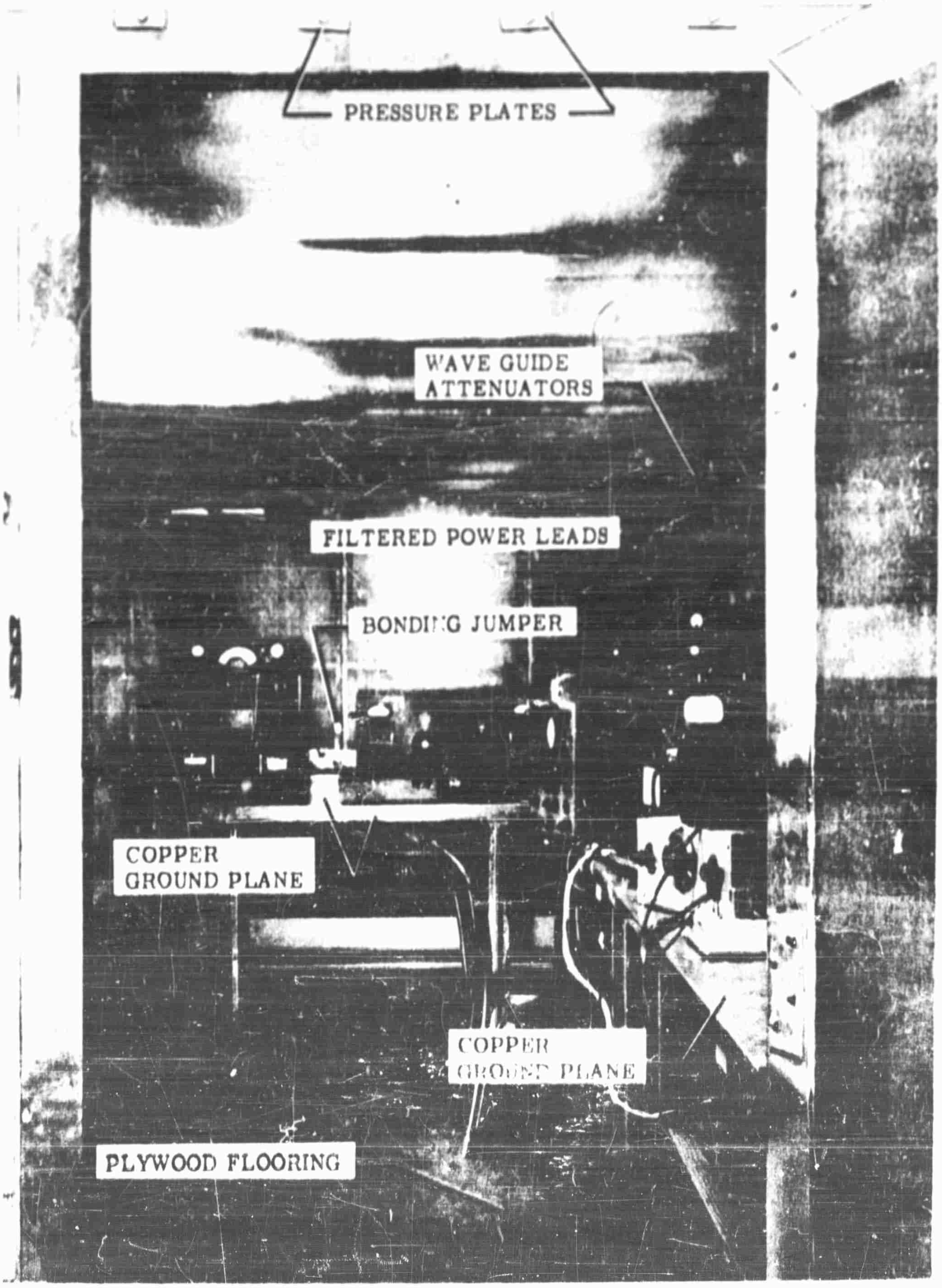


FIGURE 4 - Doorway View of Screen Room Interior

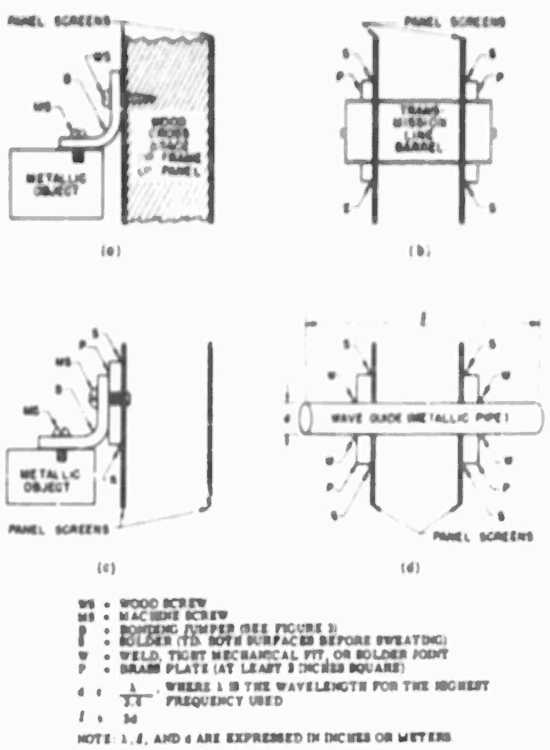


FIGURE 5 - Bonding Metallic Objects to Panel Screens

<u>Door Operation</u> - The periphery of the door is a screen room's most critical area for possible r-f leakage. The NADC-AEEL door panel design provides a leakproof door and doorframe which utilizes phosphor-bronze contact fingers and tightening wedges to eliminate all electrical discontinuities. (See figures 6, 7, and 8.) However, certain operating procedures should be observed by users of the room to assure maximum efficiency. The door should be closed slowly but firmly with evenly applied pressure; it should never be slammed shut. Both handles should be secured tightly whenever the door is closed. Handle operation should be free enough to permit the handles to assume a vertical position by gravity whenever the door is open (door handle movement can be freed by adjustment of the nuts on the handle assemblies). Attempted closing of the door with the handles in a horizontal position will damage the doorframe. The phosphor-bronze contact fingers on the door periphery should be kept clean and in good repair at all times.

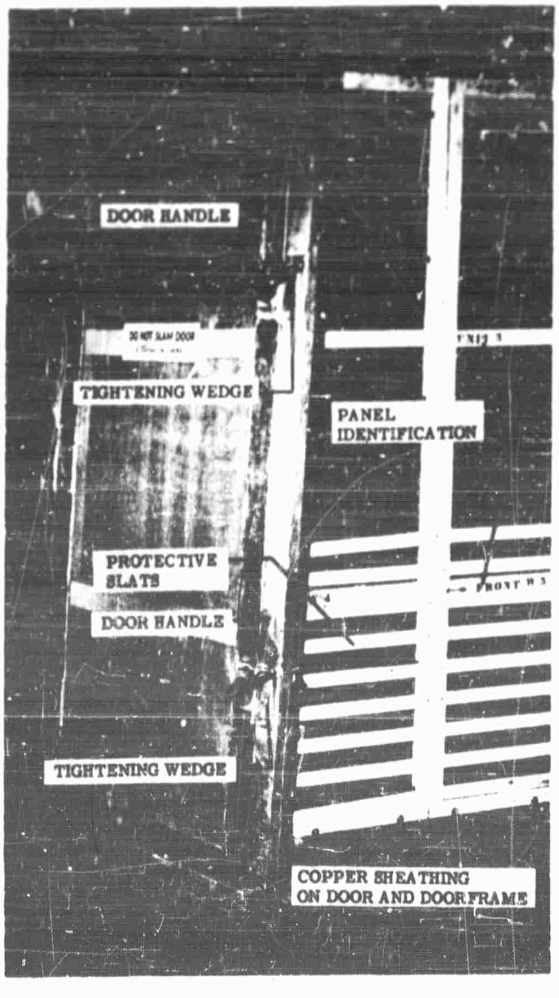


FIGURE 6 - Door and Panel Details

DISASSEMBLY

<u>Dismantling Sequence</u> - In general, the screen room should be disassembled by reversing the applicable erection sequence. If the room has been erected in accordance with the floor, walls, and ceiling sequence, the dismantling should start with the loosening of the bolts joining adjacent wall panels. This is necessary to facilitate removal of the ceiling panels.

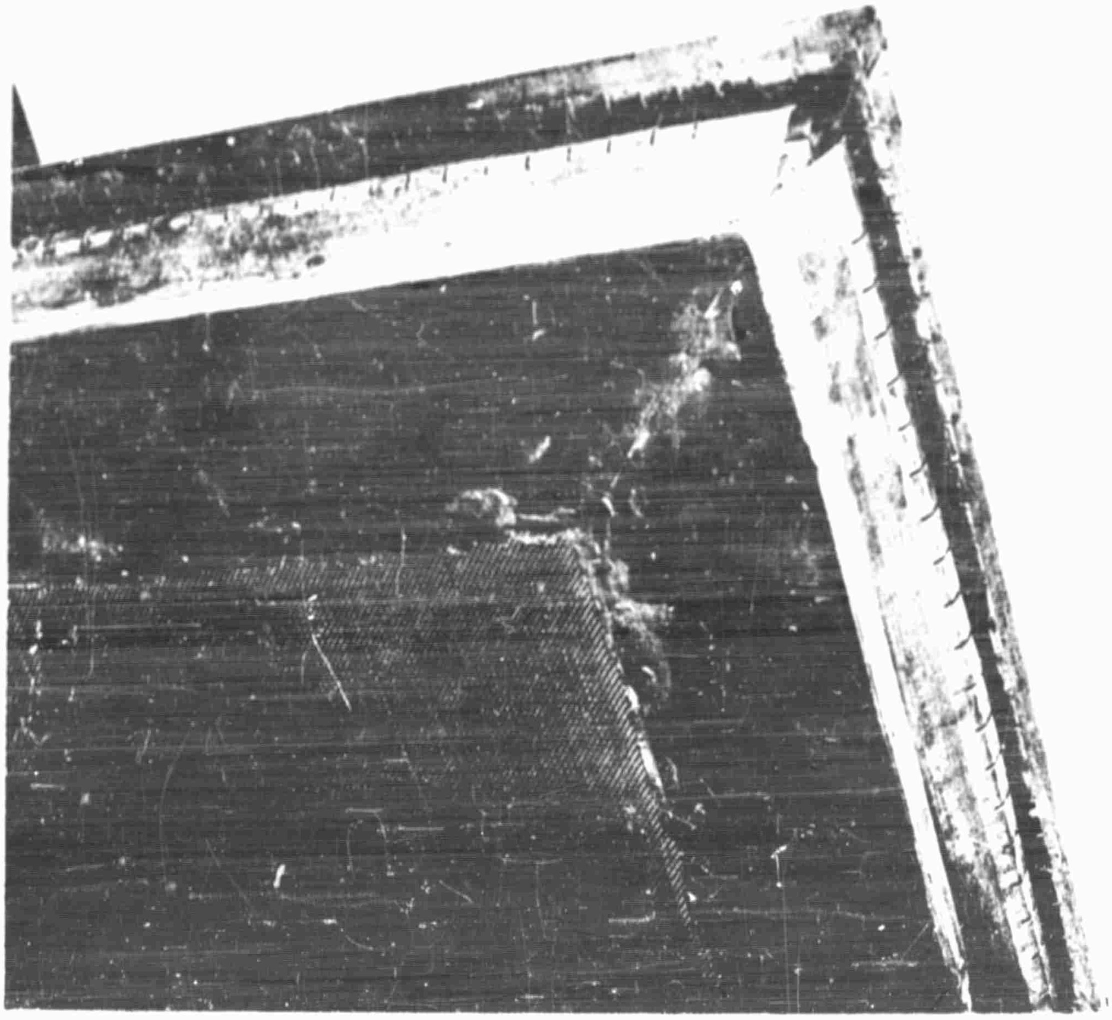


FIGURE 7 - Contact Fingers on Door Periphery

Panel Identification - The NADC-AEEL screen room includes a number of panels of identical dimensions and construction. These panels are theoretically interchangeable if they have been precision fabricated and have jig-drilled bolt holes. However, experience has shown that component panels of rooms which have been assembled for extended periods of time tend to acquire a set and are no longer interchangeable. For this reason, maximum electrical and mechanical efficiency of a screen room can be maintained only by noting the particular panel assembly pattern of the original erection and duplicating it exactly for all subsequent erections. Therefore, as shown in figure 6, the mating panels of the assembled room should be tagged, stamped, or otherwise identified, before dismantling the room the first time.

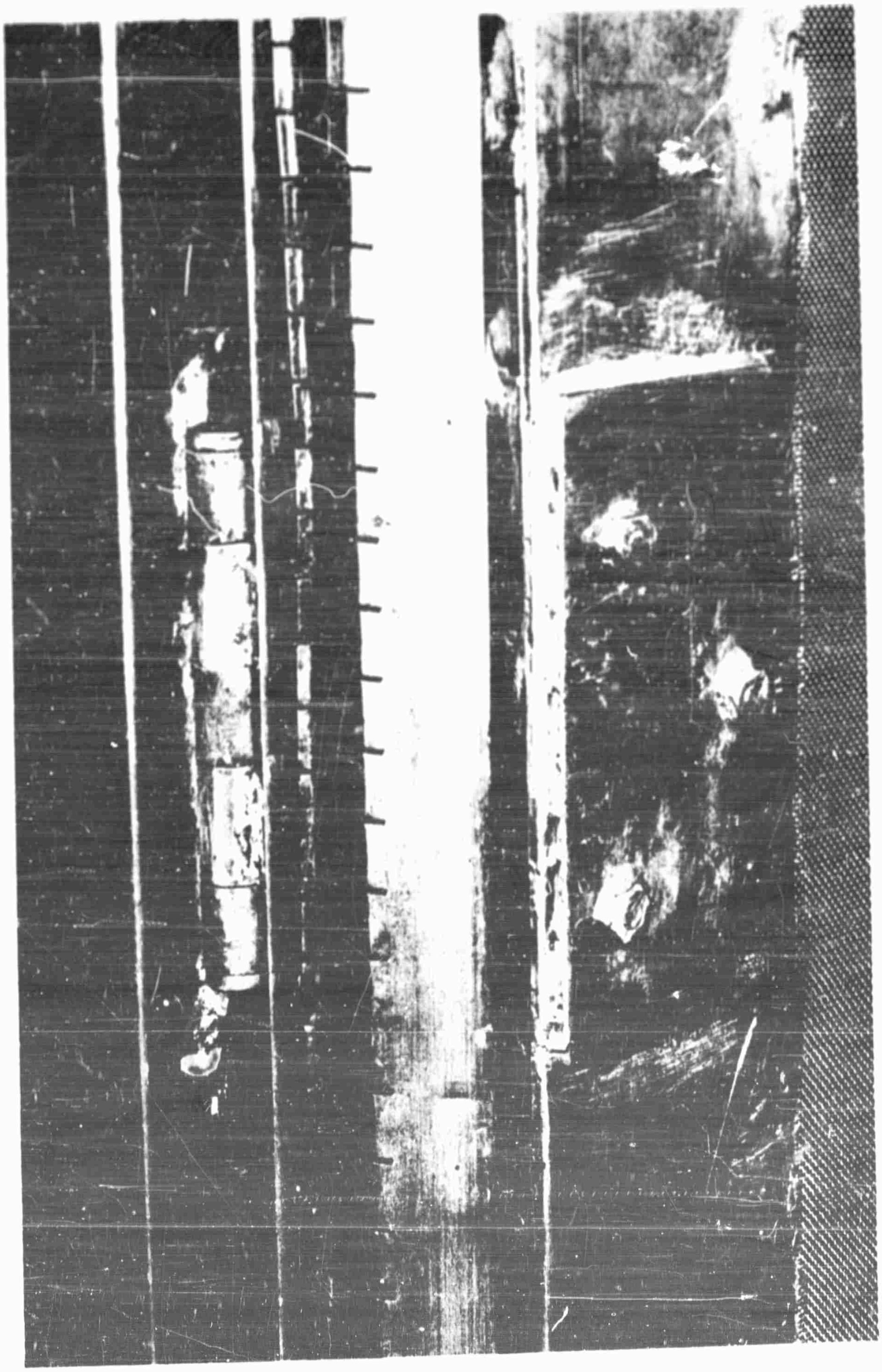


FIGURE 8 - Contact Fingers and Hinge Detail

ROOM FACILITIES AND SERVICES

POWER LINE FILTER PANEL

The NADC-AEEL screen room design includes a special panel for the installation of line filters in the power lines serving the room. The filter panel consists of a double-shielded sheet-copper insert located in one of the room ceiling panels (or wall panels, if required). (See figure 9.) The two reinforced plates of the insert are supported by the panel framework and supplement the panel screens in the area involved. The plates have the nominal 1-inch spacing of the panel screens and are bonded to the adjacent screened areas. The panel can accommodate six line filters. It also contains six waveguide-type attenuators and a common ground stud for the room. The stud can be used for the room's outside ground connection and for connection of power line neutrals.

The use of waveguide-type attenuators in the screen room filter panel is an NADC-AEEL development which provides improved power line entrances and facilitates filter installation and replacement. In use, the attenuators serve both as threaded studs for mounting the filters and as shielded conduits for carrying filter output leads into the room. Unused, they perform as true waveguide-type attenuators and do not reduce the room's nominal shielding effectiveness. Consequently, the spare or unused attenuators do not have to be capped and are available for immediate use at all times.

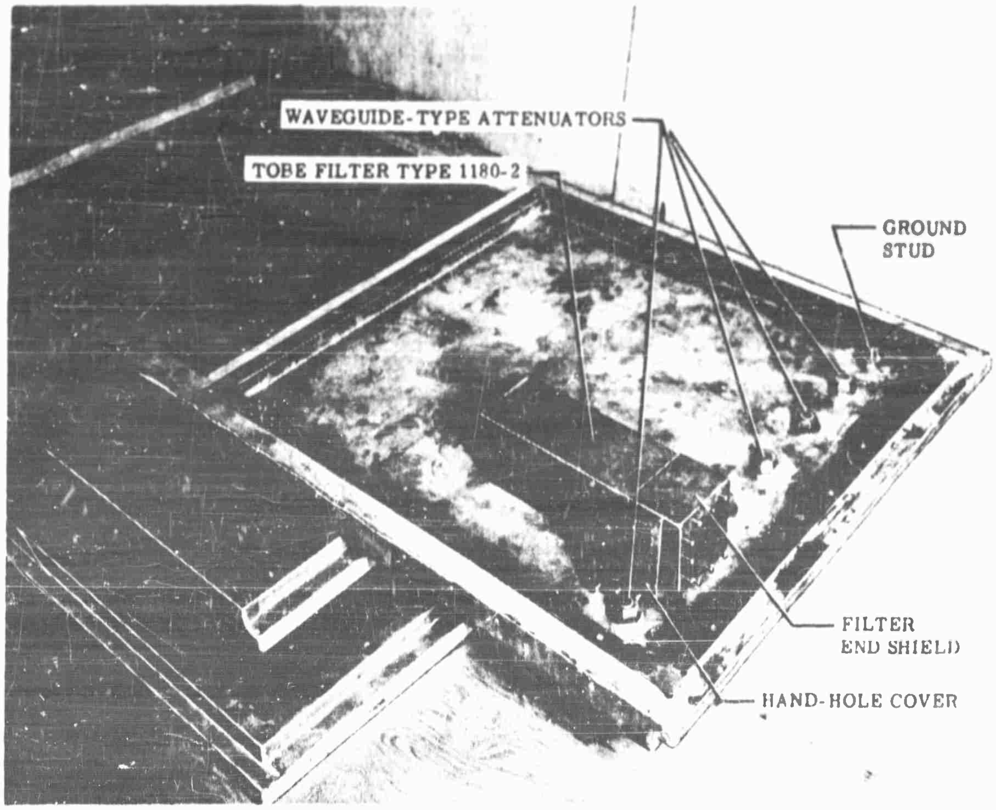


FIGURE 9 - Power Line Filter Panel

The attenuators are similar to the type illustrated in figure 5 (d). Their physical dimensions, and the highest frequency for which 100-db attenuation can be achieved, are determined by the formula shown in figure 5. For example, an attenuator approximately 1-inch long with a diameter of approximately 1/3-inch will set the highest frequency for 100-db attenuation at about 10,000 mc. The attenuators are secured mechanically and bonded electrically to both plates of the filter panel by soldering. In addition, the ends of the attenuators (both inside and outside the room) are threaded to accommodate nuts. The required type of power line filter includes an integral end shield which encloses and shields the output terminal. A clearance hole in the bottom of the end shield fits the threaded end of an attenuator and the filter is mounted to the outside of the filter panel and bonded to the attenuator by means of a single nut and lockwasher. A hand hole (with r-f leakproof cover) affords access to the end shield for attaching and tightening the filter mounting nut, for connecting the filter output lead, and for feeding the output lead through the attenuator into the room.

If the screen room has the recommended outside ground connection, only the hot lead of each pair of power leads requires filtering; the neutrals can be tied together and connected to the filter panel ground stud. However, it should be noted that this arrangement necessitates the use of polarized plugs on all removeable power cords.

POWER LINE FILTERS

The recommended power line filter is the Tobe Deutchmann Corporation Type No. 1180-2 (or equivalent). This type is adequate for power line voltages up to 500 V and for power frequencies up to 800 cps, and is shielded at the output end for input-output decoupling. It is essential that power line filters have their inputs and outputs adequately decoupled (end shields must be added to the output ends of filters not so equipped) and be properly bonded to the room's screening material.

The insertion loss of the Tobe 1180-2 filter is such that under normal laboratory conditions the nominal shielding effectiveness of the screen room is unimpaired over the frequency range of 0.15 to 10,000 mc. In severe cases, if r-f interference at frequencies above 1000 mc is present on the filtered power lines inside the room, it may be necessary to connect additional filters in series with the Tobe 1180-2 units. These additional filters should be of the coreloss, powdered-iron type of transmission line filters that can be constructed in the laboratory. Satisfactory commercial types for frequencies above 1000 mc are the Tobe Deutchmann Corporation Type No.1457, General Radio Company Type No. 874-F500 and 874-F1000, and Hopkins Engineering Company Type No. 109.

TRANSMISSION LINE CONNECTORS

Any number of single or twin coaxial transmission lines may be brought into the screen room through connectors mounted on the screened panels or on the power line filter panel. However, it is essential that these coaxial connectors be properly bonded to both screens at the point of entry. (See figure 5 and the discussion of "Bonding" in this manual.) If panel-mounting type connectors are used, their mounting plates must be bonded to the respective screens, inside and outside the room, and interconnected by a standard transmission line barrel in between the screens. When not in use, all type N and type UHF connectors should have one end capped to prevent r-f leakage into the room.

SERVICE ENTRANCES

Water, air, gas, and other special services can be brought into the screen room if required. If these services involve the use of nonmetallic lines, such as rubber hose, the individual lines must pass through metallic waveguide-type attenuators (bonded to both screens) at the point of entry. The length and diameter of each attenuator should be calculated in accordance with the formula of figure 5.

In some instances it may be necessary to power a rotating device or machine in the screen room from a power source (e.g., a motor) located outside the room, the two being connected by a rotating shaft. A nonmetallic drive shaft can be brought into the room readily through a waveguide-type attenuator. However, if the shaft is metallic it should be brought into the room through an electrically-conductive "stuffing box." This can take the form of a copper pipe of convenient length and an inside diameter approximately 2 inches larger than the shaft diameter. The pipe should extend through both screens and be properly bonded to each. The pipe ends should be threaded to accommodate threaded end caps each of which contains a shaft hole drilled sufficiently oversize to provide 1/8-inch clearance when the shaft is inserted. The stuffing box thus formed should be packed with fine shavings of some highly conductive metal such as copper, berryllium-copper, phosphor-bronze, or Monel. The end caps should be tightened sufficiently to assure good contact between the inside of the stuffing box and the running shaft.

LIGHTING

Any number of incandescent lamps may be used inside the screen room. However, fluorescent lamps must be placed outside the room (above the ceiling panels) because they are a source of r-f interference.

FANS

A-C type ventilating fans (with no sliding contacts or current interrupters) may be connected to the filtered power lines inside the room. These fans are not a source of r-f interference.

SHIELDING EFFECTIVENESS AND TEST PROCEDURES

DEFINITION

Shielding effectiveness is defined as the insertion loss (in db) in power sustained by an electromagnetic wave at a given point in space when a metal barrier is inserted between the source and that point. Shielding effectiveness as applied to metallic enclosures is a complex quantity expressed and calculated by means of formulas which take into consideration the following variables:

1. Impedance of the electromagnetic wave striking the shield. The impedance can be very low for magnetic fields, very high for electric fields, and a nominal 377 ohms for plane waves.

2. Intrinsic impedance of the shielding metal.

3. Shield thickness.

4. Shield spacing (for double-shield enclosures).

5. Frequency of the wave.

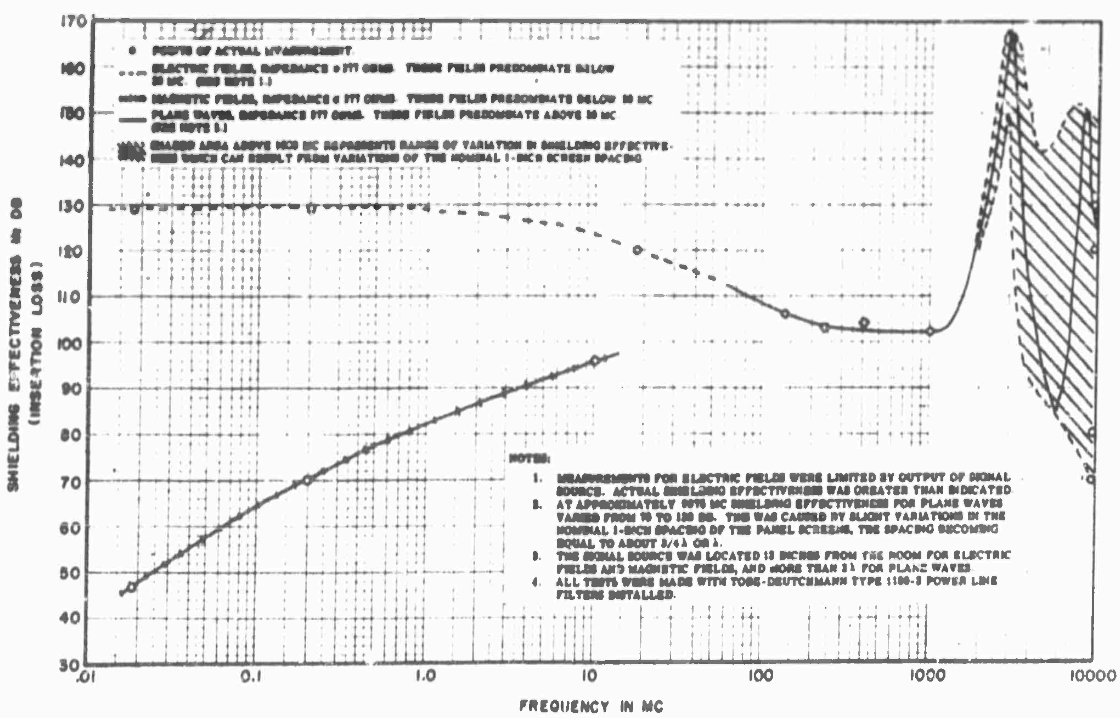


FIGURE 10 - Shielding Effectiveness of NADC-AEEL Takedown Cell-Type Screen Room (22-Mesh, 15-Mil, Copper Wire; 1-inch Nominal Spacing Between Screens)

The interacting effects of these variables are resolved into two final components, penetration (absorption) loss and reflection loss, and the sum total of these constitutes shielding effectiveness. (For complete shielding theory analyses and calculations, see Naval Air Development Center Report No. NADC-EL-54129.)

The over-all shielding effectiveness of the NADC-AEEL Takedown Cell-Type Screen Room, with power line filters connected, averages 100 db for the frequency range of 0.15 to 10,000 mc as determined by actual measurements made in the presence of various fields. Typical shielding effectiveness curves are shown in figure 10. For maximum efficiency the assembled screen room should be tested qualitatively for r-f interference leakage, and quantitatively to determine whether the nominal shielding effectiveness is being obtained.

TEST PROCEDURES

Qualitative Test - If r-f leakage has been detected, or is thought to exist, it should be located by means of a small antenna and a sensitive receiver placed inside the room and tuned to the frequency involved. The antenna should be an electrostatically-shielded, 3-inch, 1-turn loop (or 3-inch rod) connected to the receiver by means of a shielded transmission line. The line should be long enough to permit the probing of all interior surfaces of the room and the filtered power leads.

In most screen room locations, the radio interference field outside the room provides a sufficiently strong signal source for use in the test. However, in many laboratories and industrial plants this interference is sporadic and varies greatly in intensity. For instances of this sort, and in cases where the radio interference is of low level, a radio interference signal source should be provided. This can take the form of an unshielded, automobile-type ignition system (utilizing a Ford coil, a high tension coil and breaker, a magneto, etc.) or a condenser-discharge type of spark-gap oscillator.

When leakage is located, corrective measures should be taken to eliminate it or reduce it to an absolute minimum. Such measures include the tightening of panel bolts, the repairing of any screen damage, the improving of bonding of waveguide-type attenuators, the repairing or replacing of faulty power line filters, and the cleaning, repairing, or replacing of contact fingers on the screen room door. It should be noted that in some instances r-f interference may be detected at the surfaces of the panel screens inside the room, even after all possible leakage has been removed. This may be caused by the fact radio interference in some screen room locations may occasionally reach levels that exceed the room's design capabilities. It is therefore desirable to subject the room to a quantitative test.

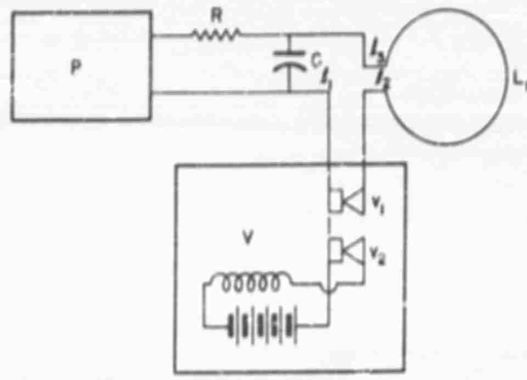
Quantitative Test - For the purpose of this manual, a simplified quantitative shielding effectiveness test is described. The test is designed for the most severe conditions affecting the room, namely, low frequencies and magnetic fields. (Tests for various frequencies and fields are included in Naval Air Development Center Report No. NADC-EL-54129, and in Specification No. MIL-S-4957.) Only a single test frequency is used and this may be chosen arbitrarily from within the 150- to 200- kc band. The known performance of the room's materials and construction together with extensive test experience have shown that if a minimum of 70 db of shielding effectiveness is achieved at the test frequency, then the nominal shielding effectiveness of the room will be satisfied over the entire 0.15- to 10,000- mc range. The following equipment and accessories are required for the test:

1. A radio interference source and loop-type transmitting antenna constructed as shown in figure 11.

2. A loop-type receiving antenna of similar construction to the transmitting loop, but equipped with a type N, 50-ohm, coaxial connector.

3. A type N coaxial connector for wall mounting. This should be installed in one of the screen room wall panels and bonded to both screens.

4. A 70-db attenuator for frequencies of 150 to 200 kc. (See figure 12.)



L_1 = TRANSMITTING LOOP, 12-INCH DIAMETER, ONE TURN NO. 6 AWG COPPER WIRE
l_1, l_2, l_3 = LOOP LEADS (AS SHORT AS POSSIBLE)
C = 1.0 UFD PAPER CAPACITOR, 600 VOLT
R = 10,000 OHM RESISTOR, 5 WATTS
P = 300 VOLT BATTERY OR RECTIFIED POWER SUPPLY
V = VIBRATOR (CAN BE MODIFIED RELAY)
V_1, V_2 = VIBRATOR CONTACTS. V_1 SHORTS OUT CAPACITOR C AT RATE OF 20 PULSES PER SECOND. V_1 IS DRIVEN BY V_2 BUT IS NOT ELECTRICALLY CONNECTED TO V_2

FIGURE 11 - Peak Power Signal Source for Magnetic Fields

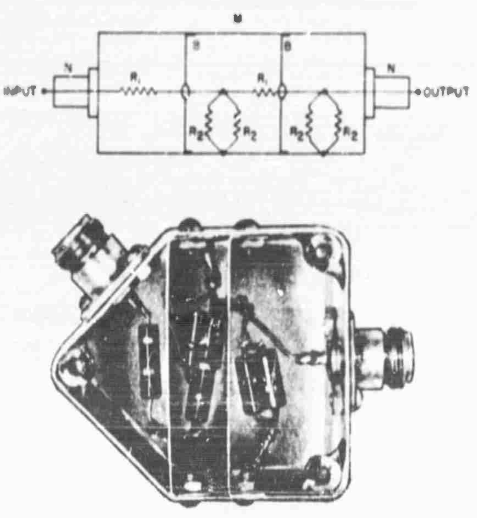
If constructed as shown in the figure, the attenuator will not require calibration and will provide an attenuation of 70 ± 1 db.

5. A receiver dummy antenna consisting of a 100-uuf capacitor enclosed in a shielded case equipped with type N coaxial connectors at each end.

6. A receiver (e.g., a type BC-348Q, a type DZ-2, etc.) covering the frequency range of 150 to 200 kc. The receiver input should be equipped with a type N coaxial connector.

7. An output meter or an oscilloscope.

8. Necessary lengths of RG-8/U transmission line and type N connectors for the test setup cables. (See figure 13(a) and (b).)



M = METALLIC CASE (BRASS OR ALUMINUM) WITH TIGHT-FITTING COVER. SUGGESTED OVER-ALL DIMENSIONS: 2 X 1-1/2 X 3 INCHES. CASE SEAMS DO NOT REQUIRE SOLDERING IF TIGHT FIT IS ACHIEVED. ALUMINUM JUNCTION BOX, NAF DRAWING NO. 1130-1, MAY BE SUBSTITUTED AS SHOWN ABOVE

B = METALLIC BARRIERS OF SAME MATERIAL AS CASE AND OF SUFFICIENT HEIGHT TO EXTEND FLUSH WITH CASE TOP. BARRIERS SHOULD BE GROUNDED TO CASE ON TWO SIDES BY SCREWS. EACH BARRIER SHOULD CONTAIN 1/8-INCH DIAMETER HOLE TO PERMIT WIRING OF NETWORK.

N = TYPE N 50-OHM SINGLE COAXIAL CONNECTOR

R_1 = 281 OHMS ±2% COMPOSITION RESISTOR

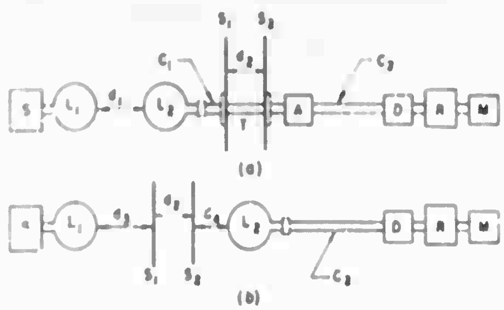
R_2 = 10 OHMS ±2% COMPOSITION RESISTOR

NOTES: 1. SLIGHTLY LOWER VALUE RESISTORS MAY BE SELECTED AND NOTCHED (BY FILING) TO ACHIEVE CORRECT VALUE AS MEASURED ON A WHEATSTONE BRIDGE.
2. NETWORK LEADS SHOULD BE AS SHORT AS POSSIBLE. USE MINIMUM AMOUNT OF HEAT WHEN SOLDERING NETWORK.

FIGURE 12 - Seventy-db Attenuator (150 to 200 kc)

The test should be performed in accordance with the test setups of figure 13(a) and (b) and the following procedures:

a. Set up the equipment as shown in figure 13(a).



S - SIGNAL SOURCE SHOWN IN FIGURE 11
L_1 - TRANSMITTING LOOP ORIENTED AT ANY ANGLE IN A PLANE PERPENDICULAR TO SCREEN ROOM WALL
d_1 - 25 INCHES
L_2 - RECEIVING LOOP (SAME AS L_1 AND POSITIONED IN SAME PLANE AS L_1)
C_1 - RG-8/U CABLE, 10 TO 12 INCHES LONG
S_1 - OUTER SCREEN
d_2 - 1-INCH SEPARATION
T - 50-OHM TYPE N COAXIAL CONNECTOR
S_2 - INNER SCREEN
A - 70-DB ATTENUATOR SHOWN IN FIGURE 12
C_2 - RG-8/U CABLE, 20 FEET LONG
D - DUMMY ANTENNA (100 UUF CAPACITOR CONNECTED IN SERIES WITH RECEIVER INPUT)
R - RADIO RECEIVER
M - OUTPUT METER OR OSCILLOSCOPE
d_3 - 12 INCHES
d_4 - 12 INCHES

FIGURE 13 - Practical Insertion-Loss Test Setup

b. Turn the equipment on and adjust the receiver gain so that the change in receiver output, as shown on the output meter or oscilloscope, is slightly above the background (but considerably below saturation) when the signal source is alternately turned off and on. If no output signal above receiver background is obtained, it indicates that the particular receiver used is not sensitive enough, or that the source does not provide a strong enough signal. After the receiver gain setting has been established, record the output indication as a reference level.

c. Without changing the receiver gain setting, set up the equipment as shown in figure 13(b).

d. Read the receiver output and compare it with that produced by the previous test setup. The output indications should be the same for both test setups if the shielding effectiveness of the screen room is the required 70 db. An increase in the output indicates a shielding effectiveness of less than 70 db; a decrease indicates a shielding effectiveness of more than 70 db.

Notes:

1. In order to perform a true insertion-loss test in the test setup of figure 13, above, the minimum allowable length for cable C_1 (figure 13(a)) is 10 inches. This length is necessary to prevent the presence of shield S_1, S_2 from affecting loops L_1 and L_2. When C_1 is at least 10 inches long, shield S_1, S_2 is effectively removed from the signal path and merely serves to shield the measuring instruments.

2. To check leakage in each of the above test setups, momentarily remove the receiving loop and cap the transmission line and ground its center conductor. Under this condition the switching on and off of the signal source should produce no change in the receiver output. If a change is observed, it indicates serious leakage through the attenuator case, dummy antenna case, or the receiver case. Any such leakage should be eliminated before conducting the test.

MAINTENANCE

GENERAL

The NADC-AEEL Takedown Cell-Type Screen Room requires a minimum of maintenance under normal laboratory and industrial plant conditions. Oxidation of mating metallic surfaces and the loosening of panel bolts are the chief sources of deterioration and preventive maintenance measures for these are relatively simple. Tests of rooms subjected to more than 7 years of continuous service have shown negligible decrease in shielding effectiveness (between 1 and 3 db). However, it is recommended that the room be taken apart, cleaned, and reassembled every 3 years.

CLEANING

Panel Joints - All mating surfaces of the screen room panels should be cleaned by buffing them with a wire brush. Dust particles should be removed by means of an air blast or a dust brush.

Door Contact Fingers - The double row of phosphor-bronze contact fingers on the door should be cleaned thoroughly with steel wool and the dust particles removed. Mating surfaces of the doorframe also should be cleaned. Cleaning of the door fingers is facilitated by removing the door from the doorframe (by removing the door hinge pins) and placing the the door on sawhorses or on a bench. DC-4 compound (Dow Corning Corporation) may be used on the contact surfaces as an oxidation deterrent.

BOLT TIGHTENING

For maximum screen room efficiency it is essential that the panel mounting bolts be kept tight (correct tightening pressure is 140 inch-pounds and should be checked with a torque wrench). Bolts of a new room should be retightened after the first month of service. Bolts of a room in continuous service should be retightened at least every 2 years.

REPAIRS

Damaged Contact Fingers - In the fabrication of the screen room door the double rows of contact fingers are applied to the door periphery in the form of long serrated strips. Damaged or missing contact fingers can be replaced readily by removing the affected portion of the particular strip and replacing it with a new strip section of the proper length. The contact strips are obtainable from commercial suppliers of screen rooms.

Damaged Screens - Holes and rips in panel screens can be repaired by soldering. A hole of any size should be covered with a patch of new screening material. The periphery of the hole and the edges of the patch should be tinned before sweating.

STORAGE

Disassembled screen rooms should be stored in a cool, dry, location. Stored panels may be stacked either vertically or horizontally, but should be so arranged that the screened surface of each panel is in contact with the exposed wood framework side of the panel next to it. Supporting fixtures, such as racks, hangers, etc., also may be used. Special precautions should be taken with the door and doorframe because of the weight involved.

Measures also should be taken to protect the door contact fingers and the protruding door handles. The door and doorframe should be stored as a complete panel assembly.

MISCELLANEOUS

GENERAL

This section provides information for achieving maximum screen room efficiency under special operation and installation conditions.

INTERFERENCE AT MICROWAVE FREQUENCIES

On the average, the nominal 100-db shielding effectiveness of the NADC-AEEL Take-down Cell-Type Screen Room is maintained through the microwave region to 10,000 mc. Although this is adequate for most applications, there may be instances where inferference will penetrate the room. For example, the nominal 100-db shielding effectiveness can be reduced by as much as 30 db when the 1-inch spacing of the panel screens becomes a half wavelength (or multiples thereof) of the frequency. Also, in very rare cases, laboratory and industrial plant screen rooms may be close to powerful radar transmitters (1 or 2 megawatts peak power) being tested without dummy antennas. The interference field under these conditions would penetrate the room even though the 100-db nominal shielding effectiveness were realized. For instances such as these, the intensity of the outside interference frequently can be reduced by use of the following:

1. Solid metal sheets used as reflectors.

2. Uskon rubberized cloth sheets (U. S. Rubber Company) used as absorbers.

3. McMillan blocks or sheets (The McMillan Company) used as absorbers.

The shielding effectiveness of the NADC-AEEL room falls off rapidly above 10,000 mc, which is about the upper frequency limit for enclosures constructed of 22-mesh screening material. Powerful interference sources seldom exist above 10,000 mc. However, where required, high shielding effectiveness for the still higher frequencies can be obtained from cell-type rooms constructed of sheet copper. These rooms can provide several hundred db of shielding effectiveness, but they require rather elaborate systems for ventilation and air conditioning (with waveguide-type attenuators operating below cut-off as intake and outlet ducts) and in some instances may introduce the psychological factor of claustrophobia for personnel using the rooms.

INTERFERENCE BELOW 150 KC

The NADC-AEEL room provides over 100 db of shielding effectiveness from 150 kc down to 10 kc, for electric fields and plane waves, but shielding effectiveness for magnetic fields drops rapidly below 150 kc and at 18 kc is only 47 db. However, the shielding effectiveness for magnetic fields can be improved somewhat by:

1. Increasing the distance between the signal source and the room. Relocating the room is frequently the simpler procedure and a move of a few feet at these frequencies can result in a considerable improvement.

2. Increasing the attenuation of the power line filters by connecting additional filters in series. The additional filters should have good attenuation characteristics below 150 kc.

The room is not suitable for the very low frequencies, from 10 kc to 60 cps, because the shielding effectiveness afforded in this region is negligible both in reflection loss and penetration loss. Adequate shielding effectiveness at these frequencies requires an enclosure constructed from solid sheets of magnetic type materials.

PROXIMITY OF INTERFERENCE SIGNALS

The nominal shielding effectiveness of the NADC-AEEL room can usually be obtained regardless of the proximity of outside interference sources. However, it is desirable to keep all such interference sources at least 12 inches from the room. Outside power lines also should be kept 12 inches away and power lines serving the room should be run perpendicular to the room walls as far as possible before connecting to the power line filters. If these lines must be run closer than 12 inches at some points, it may be necessary to connect additional filters in series at these points. For proper decoupling, the series connection between these filters should be shielded and the shield and the filter cases bonded to the panel screens.

CIRCULATING CURRENTS

The outside screens of the screen room panels should be kept from touching or connecting to metallic objects such as pipes, girders, etc. This is to prevent the setting up of r-f circulating currents which reduce the shielding effectiveness of the room. When it is necessary to bring several services or facilities into the room through metal lines, pipes, etc., it is desirable to bring them all in through the same screened panel. The lines and pipes should be kept as close together as possible.

PERMANENT INSTALLATIONS

The NADC-AEEL room can be used in permanent installations with a minimum of maintenance, mostly bolt tightening. In some permanent installations, however, the room is sealed permanently within additional walls, partitions, etc., making bolt tightening after erection impossible. For installations of this type, all mating seams between panels must be soldered continuously from inside the room (not spot-soldered) before the room is installed within the additional walls or partitions.

PORTABLE ROOMS

The takedown feature of the NADC-AEEL design makes the screen room portable only as a series of disassembled panels. It is not portable when assembled and should never be moved in such form. However, a small size room (minimum length dimension) can be made readily portable by erecting it on a movable platform equipped with wheels or casters.

PROTECTIVE SLATS AND PANELS

If the panel outer screens are subject to frequent accidental damage they can be protected by wood slats (figure 6) or by sheets of plywood or Masonite.

NOTICES TO PERSONNEL

Door Operation - Because of the importance of proper operation of the screen room door, the following notice (figure 6) is suggested for promiment display on both door surfaces:

"DO NOT SLAM DOOR - CLOSE SLOWLY"

General Notice - The accuracy and validity of all measurements and tests conducted within the screen room are greatly dependent upon proper operation and maintenance of the screen room itself. For this reason it is necessary that all personnel using the room be thoroughly familiar with the erection, maintenance, and operation procedures contained in this manual. It is therefore strongly recommended that the following notice appear on one of the interior walls of the room:

"FOR AUTHORIZED PERSONNEL ONLY. DO NOT HANDLE, ERECT, DISMANTLE, RELOCATE, OR USE THIS SCREEN ROOM WITHOUT DIRECTION"

MODIFICATIONS

No screen room modifications should be undertaken until all details involved have been discussed with and authorized by qualified engineering personnel familiar with the basic design of shielding enclosures.

ADDITIONAL INFORMATION

Detailed information on screen room theory, construction (including drawings), tests, and maintenance is included in Naval Air Development Center Report No. NADC-EL-54129. See Specification No. MIL-S-4957(Aer) for military requirements for screen rooms.

D I S T R I B U T I O N L I S T

This report is being distributed to the following activities for information, as directed by Bureau of Aeronautics letter Aer-TD-414 ser 82972 of 11 Jun 1952 and subsequent revisions, to Commander, NADEVCEN, Johnsville, Pennsylvania. The Copy Numbers apply to only classified reports.

	Addressee	No. of Copies
		1
1	CNO, OP-42	2
2,3	CNO, OP-341D	1
4	CNO, OP-551.	2
5,6	BUAER, TD-414.	
7,8,9	BUAER, TD-410, for transmittal to	5
10,11	ASTIA	2
12,13	BUAER, EL	1
14	BUSHIPS, Code 853.	1
15	BUORD, Re8e.	2
16,17	NATESTCEN, ET Div.	2
18,19	NAMTC, Code 324.	1
20	NRL, Code 1120	1
21	COMOPDEVFOR.	1
22	U. S. Naval Post Graduate School	2
23,24	NEL.	2
25,26	ONR, Code 427.	
27	Office of Chief Signal Officer,	1
	Pentagon Bldg	1
28	WADC, WPAFB, Dayton, Ohio.	
29	Cambridge Research Center, 230 Albany St.,	1
	Cambridge 39, Mass.	
30	Signal Corps, Eng. Lab, Fort Monmouth, N. J.,	1
	Navigation Br	
31	Air Research and Development Command,	1
	Baltimore, Md., RDSTIS.	

U. S. NAVAL AIR DEVELOPMENT CENTER, JOHNSVILLE, PA.
AERONAUTICAL ELECTRONIC AND ELECTRICAL LABORATORY

Final Report: Theory, Design, and Engineering Evaluation of R-F Shielded Rooms; by C. S. Vasaka

Fundamental shielding theory for cyclindrical and spherical shields is considered and reconciled with design parameters and performance characteristics of the plane-surface shields of shielded enclosures. Formulas, correction factors, and tables are included for calculating shielding effectiveness of sheet metal enclosures and screen rooms. Shielding effectiveness tests are described for various fields and frequencies. The NADC-AEEL Takedown Cell-Type Screen Room is described and evaluated.

1. Report NADC-EL-54129
2. TED Proj ADC EL-538

U. S. NAVAL AIR DEVELOPMENT CENTER, JOHNSVILLE, PA.
AERONAUTICAL ELECTRONIC AND ELECTRICAL LABORATORY

Final Report: Theory, Design, and Engineering Evaluation of R-F Shielded Rooms; by C. S. Vasaka

Fundamental shielding theory for cyclindrical and spherical shields is considered and reconciled with design parameters and performance characteristics of the plane-surface shields of shielded enclosures. Formulas, correction factors, and tables are included for calculating shielding effectiveness of sheet metal enclosures and screen rooms. Shielding effectiveness tests are described for various fields and frequencies. The NADC-AEEL Takedown Cell-Type Screen Room is described and evaluated.

1. Report NADC-EL-54129
2. TED Proj ADC EL-538

U. S. NAVAL AIR DEVELOPMENT CENTER, JOHNSVILLE, PA.
AERONAUTICAL ELECTRONIC AND ELECTRICAL LABORATORY

Final Report: Theory, Design, and Engineering Evaluation of R-F Shielded Rooms; by C. S. Vasaka

Fundamental shielding theory for cyclindrical and spherical shields is considered and reconciled with design parameters and performance characteristics of the plane-surface shields of shielded enclosures. Formulas, correction factors, and tables are included for calculating shielding effectiveness of sheet metal enclosures and screen rooms. Shielding effectiveness tests are described for various fields and frequencies. The NADC-AEEL Takedown

1. Report NADC-EL-54129
2. TED Proj ADC EL-538

U. S. NAVAL AIR DEVELOPMENT CENTER, JOHNSVILLE, PA.
AERONAUTICAL ELECTRONIC AND ELECTRICAL LABORATORY

Final Report: Theory, Design, and Engineering Evaluation of R-F Shielded Rooms; by C. S. Vasaka

Fundamental shielding theory for cyclindrical and spherical shields is considered and reconciled with design parameters and performance characteristics of the plane-surface shields of shielded enclosures. Formulas, correction factors, and tables are included for calculating shielding effectiveness of sheet metal enclosures and screen rooms. Shielding effectiveness tests are described for various fields and frequencies. The NADC-AEEL Takedown

1. Report NADC-EL-54129
2. TED Proj ADC EL-538